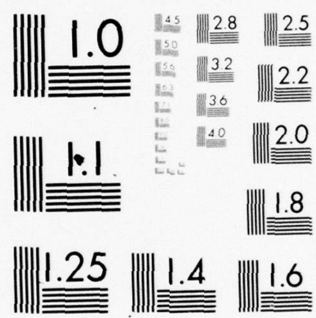
AD-A048 178 QUEENSLAND UNIV BRISBANE (AUSTRALIA) DEPT OF ELECTRI--ETC F/G 17/2.1
PRINCIPLES OF PROTECTION OF GROUND BASED RADIO STATIONS AND OTH--ETC(U)
JUN 77

UNCLASSIFIED EE77/5 NL

1 of 1

ADA048 178

END
DATE
FILMED
1-78
DDC


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0

UNIVERSITY OF QUEENSLAND
BRISBANE, AUSTRALIA

6

DEPARTMENT OF ELECTRICAL ENGINEERING

(6)

AR 000 1052

UNIVERSITY OF QUEENSLAND
DEPARTMENT OF ELECTRICAL ENGINEERING

(11) June, 1977

(12) 85p.

(6)

PRINCIPLES OF PROTECTION OF GROUND BASED RADIO STATIONS AND OTHER INSTALLATIONS FROM DAMAGE BY LIGHTNING.

(14) EE77/5
TN-2/77

This document has been prepared as

ROYAL AUSTRALIAN NAVY
DIRECTOR GENERAL NAVAL DESIGN
TECHNICAL NOTE NO. 2/77

for the DGND under contract ~~CAPO~~ Q 260002.

by

D. Mackerras, T.M. Parnell, R.A. Barham
and M.W. Gunn of the Electrical Engineering
Department, University of Queensland,
Brisbane, Australia, 4067.

New 410509

LB

PRINCIPLES OF PROTECTION OF GROUND BASED RADIO STATIONS AND OTHER INSTALLATIONS FROM DAMAGE BY LIGHTNING

ABSTRACT:

The primary purpose of this manual is to supply recommendations for the protection of vulnerable equipment in Naval H.F. radio stations from the damaging effects of lightning strikes in areas of relatively high lightning incidence. The recommendations, which can be applied to any installation containing electronic equipment operating in a high lighting-incidence area, include methods of interception of direct strokes, protection against induced current and voltage surges, and protection against ground currents due to lightning.

The expected number of lightning strikes per year to an installation may be based on the thunderday level for the region. This information may be combined with the statistical distributions of peak current in lightning flashes to predict the frequency of occurrence of injected currents of various magnitudes. Adequate earthing arrangements, depending on the local soil resistivity, will prevent excessive potentials within or between various parts of an installation. With suitably placed grounded overhead shield wires, it should be possible to prevent to direct strikes to any vulnerable part of an installation excepting antennas. Receiving antennas are vulnerable, and special measures may be needed to protect connected equipment. Measures are recommended to protect R.F. feeder runs to both transmitting and receiving antennas from direct strike. Power and signal conductors may be subjected to induced surges even when protected from direct strike. Protection of connected equipment can be achieved by surge diverters, gas arresters, current limiting series impedances, and various forms of secondary protection.

The recommended protectives measures should reduce damage to vulnerable equipment and increase personnel safety in a high lightning incidence area.

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Features of the lightning discharge to ground

The following description of the lightning discharge, and its effects on structures is the result of research carried out intermittently in various parts of the world since the eighteenth century. Many aspects of the phenomena are still poorly understood, and experts differ in their explanations and theories. Even apparently simple measurements, such as counting the number of lightning discharges in a given area and time interval, or measuring current waveshapes in lightning, have proved difficult to carry out. Nevertheless sufficient is known to specify protective measures for installations which will ensure a reasonable degree of immunity from lightning damage. A glossary is provided for the reader unfamiliar with the terms used in describing lightning phenomena, (p. 63).

A lightning discharge to ground injects into the stricken point a current typically about 20kA, and occasionally in excess of 100kA. The current rises to peak value in a few μs and has a maximum rate of rise typically 10^{10} As^{-1} and occasionally up to 10^{11} As^{-1}. This current is for practical purposes independent of the impedance to ground at the stricken point. Thus the voltage rise produced in an engineering structure is calculable from the impedance presented to the assumed lightning current waveshape, and may well be a few MV for elevated structures. The high initial rate of rise and peak value of the lightning current is followed by a variety of current waveshapes, of lesser magnitude but longer duration.

Detailed descriptions of the lightning discharge are given in references [1] to [5]. A typical lightning flash to ground consists of several separate strokes, each of which injects a separate current impulse lasting less than 1ms into the stricken point. The time interval between strokes is about 50ms. During most interstroke intervals the injected current falls almost to zero, but in about 50% of flashes, a stroke is followed by a continuing current of about 200A lasting about 100ms. The complete current waveshape passing through a resistive portion of an engineering structure will cause heating by the injection of 10^3 to 10^7 J per ohm of resistance. This may cause melting of thin metal structures, or burning of resistive materials.

A knowledge of the detailed structure of the complete lightning discharge is not usually required for purposes of determining protection of equipment, as damage, if any, usually occurs at the beginning of the first stroke. However the subsequent current waveshape contributes to energy

injection, and there may be special situations where the effects of continuing currents,or the effects of several successive strokes in a single discharge, should be considered.

Any conductor near a lightning discharge path, or near another conductor struck by lightning, will have a voltage surge induced in it by electric and magnetic coupling. These surges involve less voltage and energy than those caused by a direct strike, but may be sufficient to damage some classes of equipment.

Lightning strikes to ground near an installation may cause currents to enter the installation through earth connections. The amount of current will be a fraction of the current injected by the lightning stroke; the fraction being determined by the resistivity and structure of the ground, and the distance from the lightning strike to the earth connections. This will cause the installation local earth potential to rise, and may cause an excessive voltage difference between the local "earth" and incoming conductors from other parts of the installation, unless suitable protective devices limit the voltage difference.

Thus the threat of lightning damage to engineering structures and equipment can be described in terms of excessive voltages and currents caused by a direct strike, by induced surges, and by ground currents.

1.2 Variability of thunderstorm and lightning characteristics

The recommendations contained herein apply primarily to areas of relatively high lightning incidence, implying a thunderday level greater than 40 per year, and a corresponding number of lightning flashes to ground per unit area and per year (ground flash density) greater than 2 km^{-2} yr^{-1}. The extent to which the recommendations are applied in areas of lesser lightning incidence will depend on economic factors, and the importance of the continuity of the service provided. It is a matter of observation that there are large year-to-year variations, so it must be expected that occasionally an installation will be struck by lighting far more often than would be expected from the long-term average. These periods of high incidence will occur in intense thunderstorms of a few hours duration. Thus it would be unwise to assume that lightning strikes to an installation will always occur singly in time, with opportunity to repair damage following the strike. The more conservative assumption is a long period of inactivity followed by a short period with several strikes in succession and no opportunity to repair damage between strikes.

There are substantial variations in the estimates of lighting parameters made by investigators of lightning. The values of parameters stated here and assumed in calculations are selected so as to result in conservative recommendations. It follows from this uncertainty regarding the characteristics of lightning, and the frequency with which any given installation will be struck, that precise calculations of currents, voltage, and imparted energy in a particular equipment are not usually justified. It is generally sufficient to make order-of-magnitude calculations to determine the level of protection necessary in a particular situation and then adopt a standardised set of protective measures.

1.3 Protection of an installation

1.3.1 Justification for lightning protection

The decision as to the extent of lightning protection justifiable for any particular installation is an economic one which must be based on a comparison of the additional cost of providing the protection, the estimated cost of repairing unprotected damaged equipment, and the cost of an interruption to the service provided by the installation. Some factors which should be considered in this comparison are as follows.

(i) Provision of lightning protection at the time of designing the installation and specifying the associated equipment may be cheaper than provision of equivalent protection after the completion of the installation.

(ii) A single lightning strike may simultaneously damage several parts of an unprotected installation.

(iii) The provision of lightning protection has incidental benefits, such as minimising equipment malfunction caused by switching surges.

(iv) The general trend towards replacing vacuum tube devices by solid state devices increases the need for surge protection. Vacuum tubes can withstand surge currents and voltages far in excess of steady-state ratings whereas solid-state devices are more vulnerable to transient overvoltages and transient excess energy injection. Protective measures satisfactory with vacuum tube equipment may not be adequate with solid-state equipment.

(v) Provision of lightning protection will increase the personal safety of those who have to operate equipment during thunderstorms.

1.3.2 *Strategy of lightning protection*

The basic strategy in protecting an installation is as follows:

(i) Provision of a system of overhead earthed conductors to intercept direct lighting strikes as far as is technically permissible.

An overhead earthed conductor plays an active role in diverting a lightning stroke. The first stroke of a lighting flash is initiated by a leader which progresses from the thundercloud towards earth. Normally, the leader conveys negative charge from the thundercloud, and during its progression to earth deposits negative charge in a sheath along its path. When the leader tip is about 100m from earth, the electric field at the earth's surface caused by the leader charge rises to such a high value that breakdown occurs at elevated objects on the ground especially if their shape tends to increase the local electric field. The resulting streamers progress towards the tip of the downcoming leader. Several such streamers may start, but usually only one reaches the downcoming leader. When this happens the high-current return stroke commences. The successful streamer may move laterally for tens of metres, as well as upward, thus effectively diverting the lightning from the path which would have been followed in the absence of the elevated object.

(ii) For structures whose function would be adversely affected by an overhead conductor, provision of means for diverting the full lightning current to earth.

The only structures to which this applies in radio stations are open-wire aerials and monopoles. Aerials connected to transmitters are likely to be struck periodically, and the full lightning current delivered down the RF feeder. The normal method of protection is by spark gaps, which experience has shown to protect adequately the power vacuum tubes in the final stages of transmitters. Occasional damage to balun transformers and other components between transmitter and RF feeder is accepted as inevitable.

Some aerials used for receiving are currently protected by a combination of spark gaps, fuses and neon tubes, (section 5.2). It is probable that many existing open wire aerials could have their lightning resistance improved by the minor changes detailed in sections 3.1 and 6.5.9, namely extension to supporting towers to help intercept lightning, increasing insulation between tower and aerial and replacing spark gaps by gas arresters.

The protection of monopoles from the effects of a direct strike presents a special problem. Current practice is to accept occasional destruction of the balun transformer used to couple the monopole to the coaxial cable, and to use a gas arrester to prevent damage to the cable and connected equipment.

(iii) For conductors exposed to induced surges and connected to vulnerable equipment, the provision of suitable means for diverting surge current to earth and preventing a voltage rise above the insulation level of equipment.

(iv) Provision of a system of in-earth conductors to provide a low impedance path for earth currents, thus preventing dangerous rises in local earth potential near an installation.

(v) Provision of a suitable protective components at the points of connection of signal and power conductors to equipment used in an installation. These components should preferably be included at the design stage and built into the equipment, but may alternatively be included as separate units interposed between an existing item of equipment and its signal and power connections.

Thus the methods of protection, decribed in detail below, can be summarized as surge current diversion, insulation coordination, and adequate earthing.

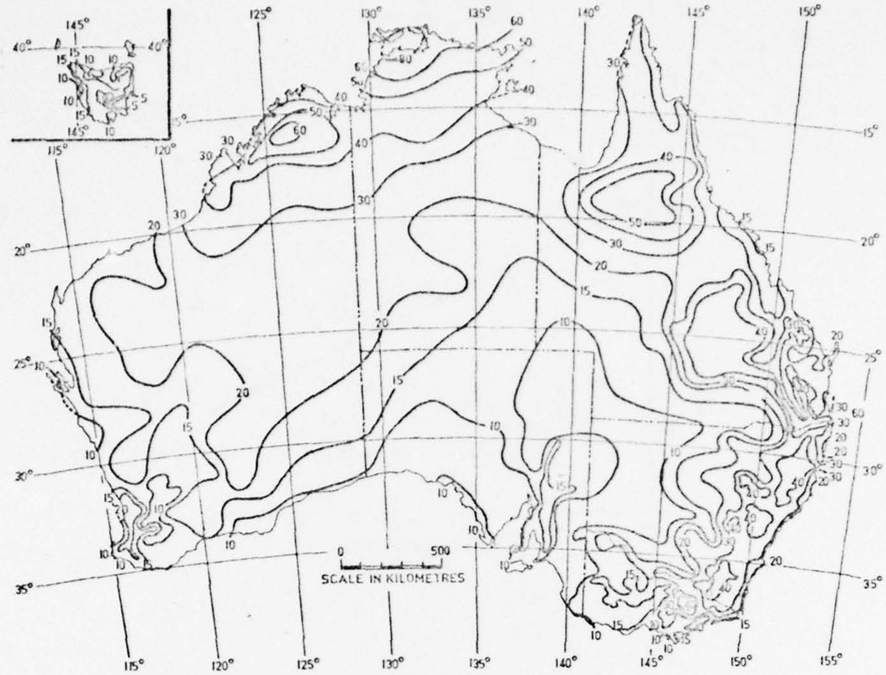


Fig. 1 *Thunderdays per year in Australia. Adapted from the thunderday map issued by the Bureau of Meteorology, Australia, based on ten years of records 1954 to 1963.*

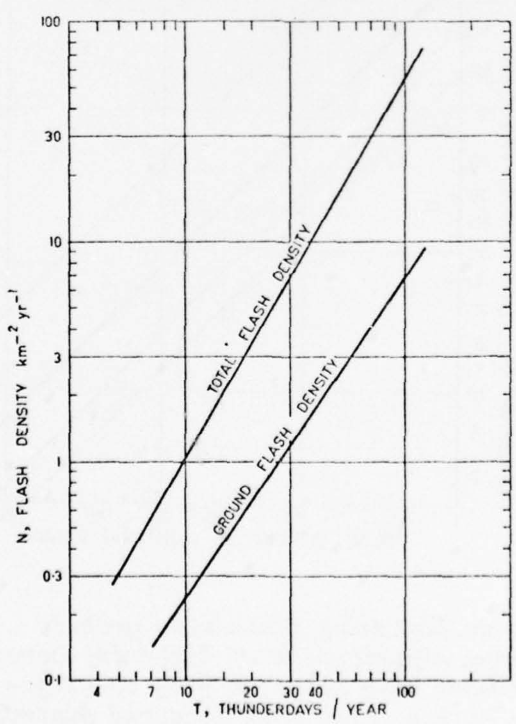


Fig. 2 *Relation between lightning flash density and thunderdays per year, based on information in [8-12].*

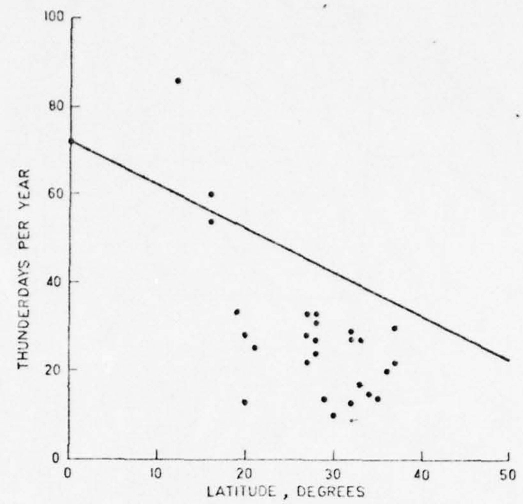


Fig. 3 Relation between latitude and thunderdays per year, [10]
Heavy Line: World Average
Points from Australian Stations [11,12]

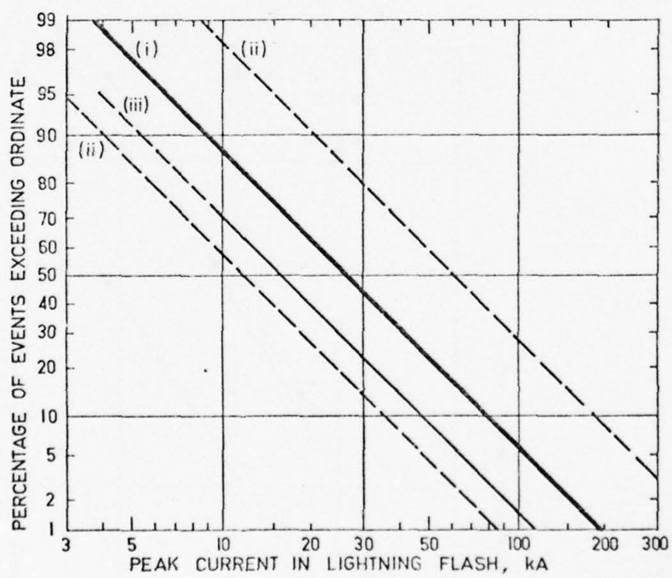


Fig. 4 Peak current in lightning flashes to ground.
(i) Frequency distribution of lightning currents to objects 20m or more high based on [13] to [22].
(ii) Limits within which most measured distributions fall, from [3].
(iii) Synthetic distribution for strokes to level ground, from [23].

2. CHARACTERISTICS OF LIGHTNING CURRENTS

The lightning current which flows in a stricken exposed structure is believed to be almost independent of the impedance of the structure. The lightning stroke is therefore represented as a current source, with peak current and waveshape characteristics occurring according to the statistical distributions given below. The frequency of occurrence of lightning strikes to a structure is related to the ground flash density, which is normally estimated from the number of thunderdays per year at the site.

2.1 Estimation of ground flash density

Thunderday levels over Australia are given in Fig. 1, based on [6].A procedure for assessing the lightning risk at any site is given in section 3.4 of [7]. This may be useful in determining the degree of lighting protection justified at a site for which no previous records of lightning incidence exist.

Ground flash density may be estimated from the thunderday level using the relation shown in Fig. 2. Where no thunderday information is available, the latitude of the site may be used in Fig. 3 to estimate these quantities. Details of the source information is given in [8] to [12]. From the above information, the expected number of lightning strikes per year to any installation is given by:

$$\text{No. of lightning strikes per year} = N_g A \qquad (1)$$

where N_g = ground flash density ($km^{-2}\ yr^{-1}$) and A = effective area of installation (km^2). In applying (1) to an area of flat open ground, A is equal to the actual area of ground under consideration.

2.2 Lightning currents in low level installations

Frequency distributions of peak current in lightning strokes have been reported in [13] to [22]. The heavy line, marked (i) in Fig. 4 gives a frequency distribution of lightning currents which is reasonably close to the majority of published measurements. The lines labelled (ii) show the limits between which most measured distributions fall. Most measurements have been made on tall towers, transmission lines, and tall buildings. In [23], by allowing for the effect of structure height on the measured distributions, the synthetic distribution of line (iii) is proposed as the frequency distribution of currents to open ground and structures less than about 5m high. From this distribution, approximately 50% of peak currents exceed 16kA, 10% exceed 45kA and 3% exceed 80kA. Considering, for example, a low-level installation covering an area of $0.5km^2$ in an

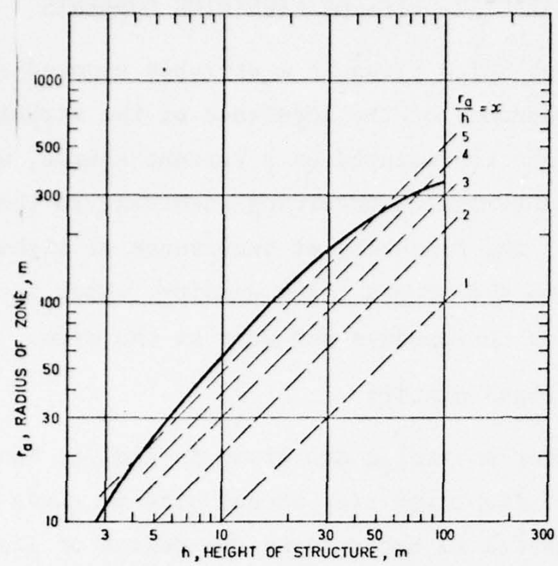


Fig. 5 *Radius of zone, r_a, over which lightning flashes are intercepted by an elevated structure of height h according to Eq. 7 in [3] $r_a = 80\sqrt{h}\,\{exp(-0.02h)-exp(-0.05h)\} + 400\{1-exp(-10^{-4}h^2)\}$, r_a and h in metres. Broken lines indicate constant r_a/h ratio.*

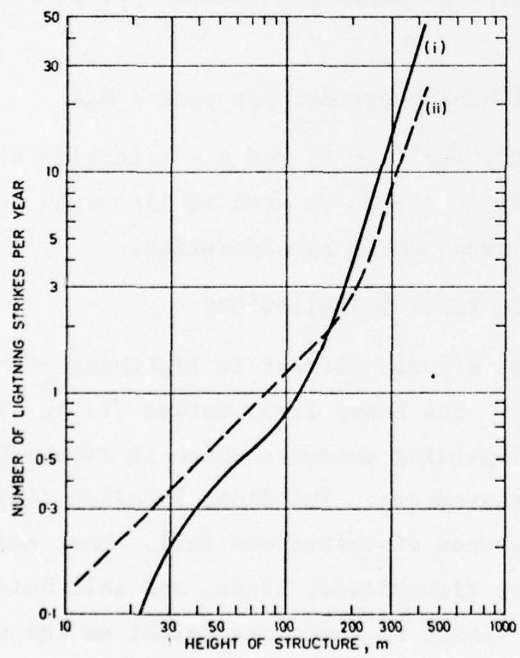


Fig. 6 *Number of lightning strikes per year to an elevated structure.*
(i) According to [3] with 32 thunderdays/year and latitude 45^o (Northern hemisphere).
(ii) According to [24] with 30 thunderdays/year.

area where $N_g = 6 km^{-2} yr^{-1}$. The installation will be struck 3 times per year, or 30 times in 10 years. Hence a peak current of 80kA can be expected somewhere in the installation every 10 years, a peak current of 45kA every 3 years, and a peak current of 16kA every 2/3 of a year. A peak current of 80kA is therefore selected as a reasonable basis for "worst case" calculations, and gives an expected protection failure rate of not more than one failure in 10 years in the above example, assuming no lightning current below 80kA causes failure.

2.3 Lighting currents in elevated structures

Any elevated structure tends to protect an area of surrounding ground, as the lightning path is diverted towards the structure. The means whereby this occurs is explained in section 1.3.2, although the details of the process are not well understood. The relation between the height of an object, h, and the extent to which the object can divert sideways the path of lightning determines the radius, r_a, of the zone over which the object is likely to intercept the lightning strike. The higher the object, the greater the size of the zone below protected from lightning. In [3] empirical relations are presented, which have been used to compute the relation between r_a and h given in Fig. 5.

It is probable that the impedance of the source supplying current to an upward streamer affects the rate of growth of the streamer. Thus a streamer fed from a low impedance source, such as the top of an earthed mast, has a greater probability of meeting the down-coming leader than a streamer fed from a higher impedance source supported by the mast, such as an aerial. Thus the mast tends to protect the aerial, even though not much higher than it.

For an installation containing elevated structures, or on a hill top, or both, the effective area is greater than the ground plan area, and may be estimated as indicated in Appendix 1. As a result, the number of lightning strikes is greater than would occur to the same area of flat ground.

For an isolated structure of height h (m), the number of strikes per year to the structures increases with h in the manner shown in Fig. 6 for a region with about 30 thunderday per year based on [3] and [24].

A further complication is that the attractive distance of an elevated object is believed to be greater for large-current strokes than for small-current strokes. The reason advanced for this is that large-current strokes are associated with large amounts of leader charge, hence large fields at ground level, hence longer upward streamers which may permit greater lateral

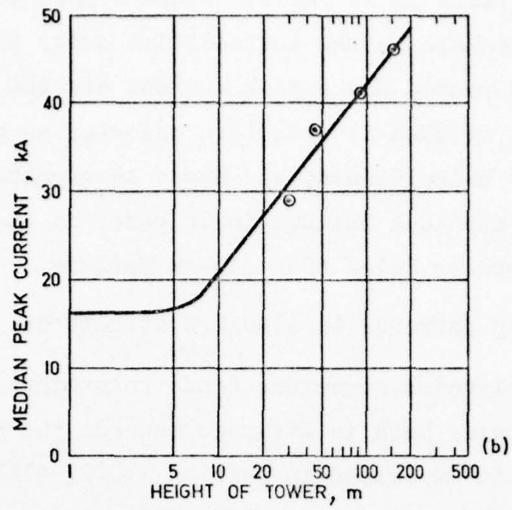


Fig. 7 Effect of tower height on median value of peak current in frequency distribution of lightning currents to tower. Marked points obtained from [23].

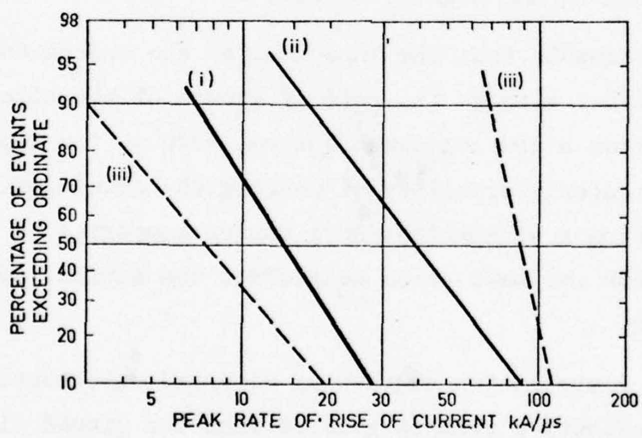


Fig. 8 Peak rate of rise of current in lightning flashes to ground.
(i) For first strokes, [13].
(ii) For subsequent strokes, [13].
(iii) Limits between most measured distributions fall, [3].

diversion of the stroke path. This affects the distribution of currents, the median current increasing with tower height as shown in Fig. 7 based on [23]. To compensate, a peak current higher than 80kA should be selected for "worst case" calculations relating to objects greater than 20m high, using line (i) of Fig. 4 to guide in the selection of "worst case" peak current.

2.4 Rate of rise of lightning current

The frequency distribution of maximum rates of rise of lightning currents is given in Fig. 8, based on [3] and [13]. Subsequent strokes have larger rates of rise of current than first strokes, but usually smaller peak current than first strokes. Thus it is usual to assume that peak current and peak rate of rise of current do not occur at the same time when the complete lightning discharge is being considered. However, when any particular stroke of the discharge is under consideration, it is quite possible for the largest rate of rise of current to occur just before the current peak, so that for conservative calculation they should be considered to coincide.

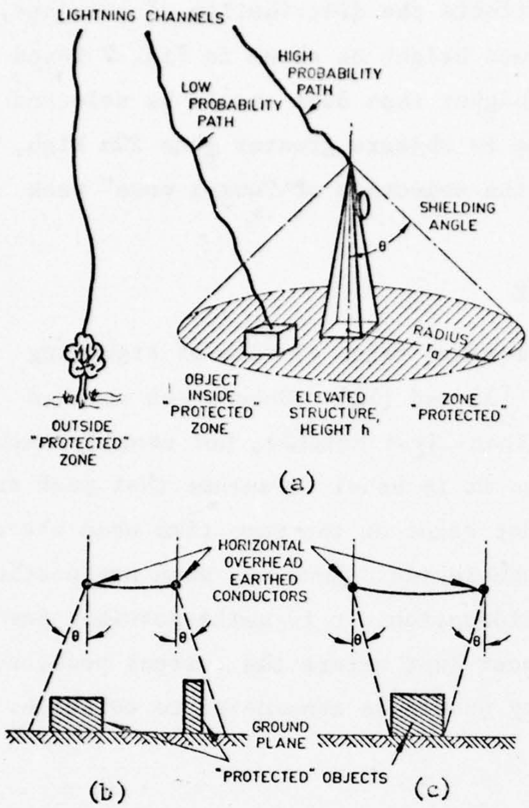


Fig. 9 Illustration of shielding angle, θ.
(a) Zone shielded by isolated structure
(b&c) Zone shielded by earthed horizontal overhead conductors.
(c) Illustrates a negative shielding angle.

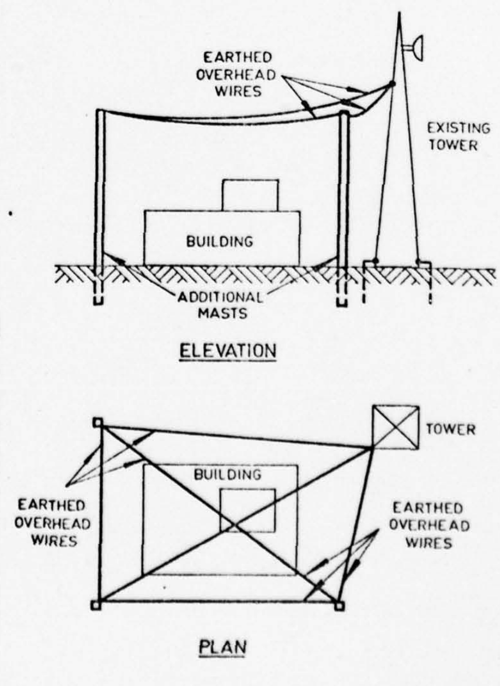


Fig. 10 Lightning protection of building by earthed overhead wires utilising an existing tower and three additional masts. Lightning current is conveyed to earth through the tower and the masts if metallic, otherwise through downleads and earth stakes.

3. INTERCEPTION OF DIRECT STROKES

Very effective low-cost lighting protection can be provided by carefully placed and properly earthed shield conductors over vulnerable installations. This takes advantage of the active role played by an elevated conductor in diverting to itself the path of the lighting stroke.

3.1 Zone of protection of an elevated conductor

Any elevated conductor having a low-impedance path to earth tends to protect objects within a certain shielding angle (Fig. 2 of [7]) as shown in Fig. 9. Experience shows that the number of shielding failures falls as the shielding angle decreases, and a maximum value of 20° is recommended for installations with vulnerable electronic equipment. In many cases, a shielding angle approaching zero or even a negative shielding angle can be obtained with little additional expense.

Some existing radio station buildings may already be partially protected from direct strike by a nearby mast or tower, used for supporting aerials or microwave antennas. In these cases the protection could be made more complete by an overhead shield wire from the existing tower to another tower or pole on the opposite side of the building (or group of buildings). This method is illustrated in Fig. 10 and has been used successfully for many years to protect electricity substations and switchyards [25]. This approach is probably cheaper than protecting the building as shown in Fig. 11 by a system of earthed conductors over the roof of the building and around its periphery and has the further advantage of keeping lightning currents away from the building. Further details of lighting protection of buildings are given in Appendix 2.

Buried coaxial cable used to connect aerials to receivers is periodically damaged by lightning ground currents, the sheath being distorted as though struck by a chisel. Similar damage to underground communication cables has been reported in [26] and [27]. Coaxial cables are sometimes run 2 or 3m above ground as a temporary measure, often strapped to a supporting wire. Inspection for fault location and maintenance are simpler in this position. These cables could be well protected from lightning by suspending them about 1.5m below the supporting wire, which then acts as an overhead shield wire. The recommended arrangement is shown in Fig. 12. Note that the clearance of 1.5 m between cable and metal support minimises the risk of flashover from a stricken support wire to the cable.
Each supporting post, at intervals of not more than 20m, drains lightning

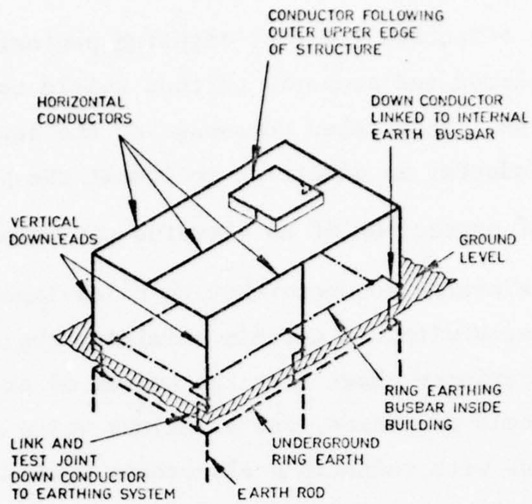


Fig. 11 Protection of building by earthed conductors attached to outer surface of building. Adapted from Fig. 5 of [7].

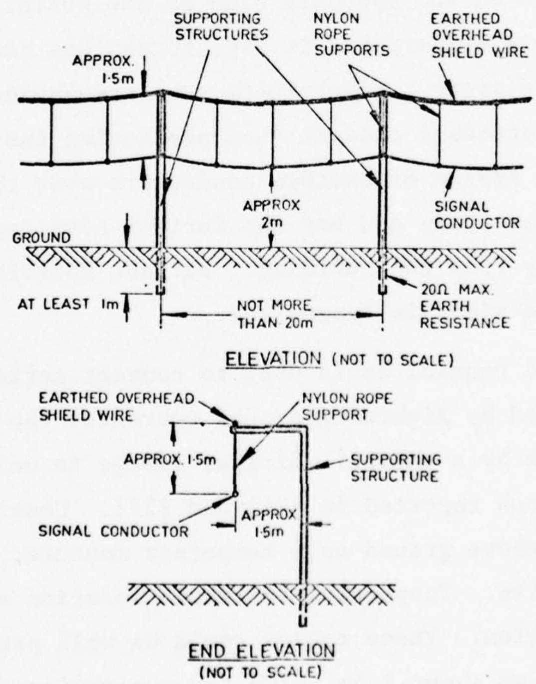


Fig. 12 Recommended arrangement of overhead signal conductor and earthed overhead shield wire.

TABLE I

Insulation strengths of strings of disc insulators.
Insulator size: 254 mm (dia) x 146 mm.

Number of insulators in string	Breakdown voltage (kV) (average values)	
	Power frequency (wet)	Negative impulse (wet or dry)
1	50	130
2	90	255
3	130	345
5	215	495
7	295	670
10	415	930
15	600	1360
20	775	1785
25	950	2210

Values extracted from NGK Insulators Catalogue Number 65.

TABLE 2

Target earth resistance for various structures.

Structure	Type of Earth Connection	Target Low-frequency earth resistance ohm		Probable approx. resistance under impulse conditions ($I_{max} \approx 80kA$)
		Med ρ	High ρ	
Large Building	Multiple Earth Stakes or Earth Mat	1	1	1
Small Building	Earth Stakes at 10m intervals around building	2	3	1.5
Medium Tower, Aerial Mast.	4 Earth Stakes at at Corners of Tower	10	20	6
Minor supporting structure eg. for shielded O/H cable run, or RF open-wire feeder	Single Earth Stake or Metal Pipe Etc. Buried ∿ 1m in Ground	20	40	8

Med ρ: Medium resistivity soil: $\rho \approx 10^2 \Omega\ m$

High ρ: High resistivity soil: $\rho \approx 10^3 \Omega\ m$

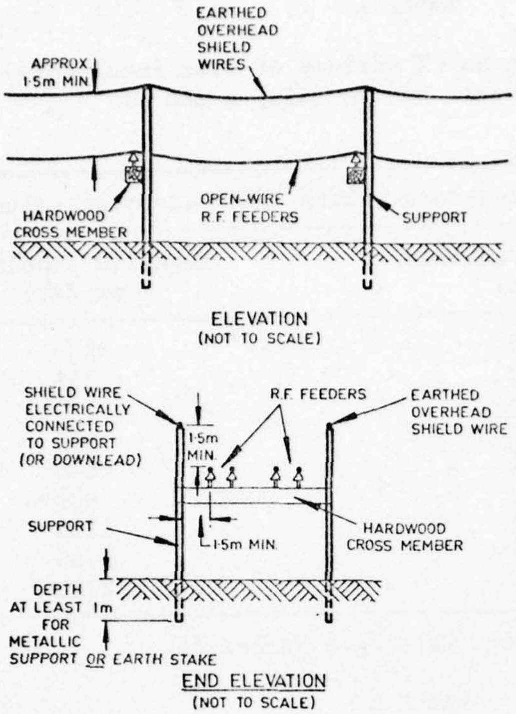


Fig. 13 Recommended arrangement of earthed overhead shield wires for open-wire RF feeders. Earthing is effected through support structure if metallic, otherwise through down conductors and earth stakes at each support.

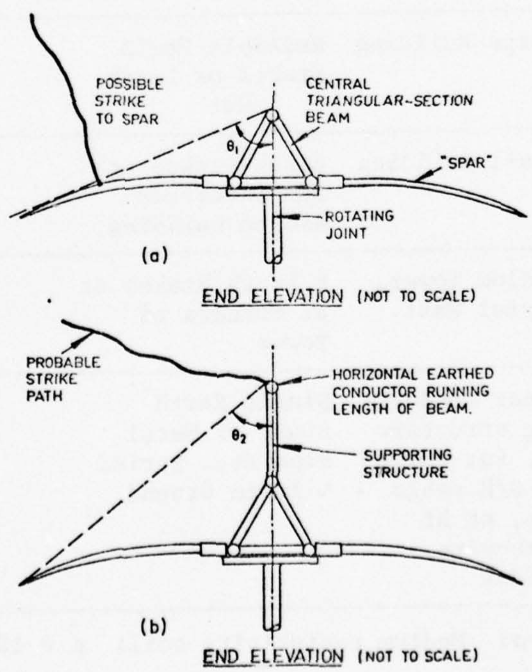


Fig. 14 Improved lightning protection of log-periodic array by horizontal earthed conductor above central beam, which reduces shielding angles from θ_1 to θ_2.
(a) Existing arrangement.
(b) Suggested addition to improve shielding.

current to earth. To do this effectively, the resistance to earth at each post should not normally exceed 20 ohm, see section 3.3.

Open wire RF feeders connecting transmitters to aerials are usually run on gantries. Improved lightning performance has been found to result from mounting the feeder insulators on wooden crossarms, and allowing the vertical steel pipe supports to project above the uppermost crossarm. Further protection could be achieved by extending the vertical members and running earthed overhead shield wires above the feeders as shown in Fig. 13. This arrangement is recommended for long runs of exposed RF feeder, where no protection is afforded by nearby masts and buildings. This would ensure that a direct strike would only occur to the aerial, and the energy in the stroke would be partly dissipated in the RF feeder before reaching vulnerable components.

Steerable log-periodic arrays are protected to some extent by the central beam, see Fig. 14, which is at earth potential and somewhat higher than the radiating elements. Protection could be improved by increasing the height of the top member of the beam, or by a spine running along the beam, as shown in Fig. 14(b). It would be necessary to establish that these measures did not adversely affect the performance of the antenna.

As noted in section 2.3, an open-wire aerial is to some extent protected from direct strokes by its earthed supporting masts. This protective effect could be enhanced, without detracting appreciably from the aerial performance, by mounting a vertical metal rod on top of each mast, projecting 4m above the top of the mast, and electrically connected to it. Although this would not provide complete protection, it should ensure that at least all high-current strokes strike the mast instead of the aerial wire. Some further improvement in lightning performance would result from ensuring low earth resistance at the base of each mast (e.g., not greater than 10 ohm) and increasing the insulation between aerial and mast, to a level of the order of 1MV for impulse voltages. This could be achieved by adding insulation of adequate impulse strength to the normal aerial insulation. The object of this is to prevent flashover from a stricken mast to the aerial or the downlead. The impulse strengths of strings of a typical disc insulator are given in Table 1 (p. 19).

3.2 Selection of conductors for lightning protection

The selection of conductor size is based on the requirement of low electrical resistance, mechanical strength, and resistance to corrosion. Experience has shown that the conductors listed in Appendix 2 satisfy these requirements. Selection of a suitable conductor must be based on local

environmental considerations and economics. For overhead earthwires or shield wires not directly attached to buildings, use of stranded galvanised steel wire is recommended.

For lightning conductors to be attached to buildings, preference should be given to copper strip or rod of cross section at least 50 mm^2 on the grounds of durability and ease of installation and jointing. However, conductors of much smaller cross section will carry typical lighting currents and serve to protect structures which might not be considered worth protecting to the extent recommended above, e.g. domestic dwellings. Examples of conductors are stranded copper earth wire and single strand galvanised steel wire. The method of calculating the heating effect of lightning current is given in Appendix 3. Material for earth stakes should be chosen for durability, corrosion resistance in the local environment, and mechanical strength to withstand driving to a depth of at least 1m. A stake thus chosen would have adequate cross section for carrying lightning current, simply on account of the cross sectional area needed to provide mechanical strength.

3.3 Earthing requirments

Any overhead lightning conductor system requires a low-impedance connection to earth comprising suitable down leads and an earth terminal comprising a system of driven rods and buried conductors. The details of the earthing system must be adapted to the layout of the installation and to the resistivity and structure of the ground.

All buildings should be provided with an earth having a resistance of not more than 1 ohm for a large building, 2 ohm for a small building (Table 2,p.19). Normally this can be achieved by driving stakes at intervals around the building periphery, linking each stake to a ring conductor around the building. This may be either below or above ground level and should be installed so as to avoid corrosion problems and mechanical damage. Lightning conductors fastened to the upper part of the building, should be connected to this earth by at least four down-leads. The structural metalwork of the building, and steel reinforcing rods in concrete should be electrically connected to the building earth at or near ground level. Further details of recommended building earthing are given in Appendix 4.

Towers and masts should be provided with up to four earth stakes linked to the metal work so as to achieve a resistance of not more than 10 ohm, or 5 ohm for a large tower (Table 2). Driven stakes are considered preferable to buried plates on economic grounds. Buried wire should only be necessary in areas where the earth resistivity is high (see

section 3.3.2).

It has been observed that the effective resistance of an earth connection is less under impulse conditions than under d.c. or low frequency, low voltage, conditions. In [28] the impulse earth resistance is stated to be time-dependent, and, using a model for breakdown processes in earth, the effective resistance for an 80kA impulse current is estimated to be 0.18 to 0.65 of the low frequency value for the type of earth connection normally used on a tower. This phenomenon provides an additional margin of safety in reducing tower and building potentials below the value calculated from the low-frequency earth resistance. Some reduction factors relating resistance under impulse and low frequency conditions are given in Table 3. Where an earth mat exists, building and tower earths should be bonded to this earth mat. Methods of measuring earth resistance are given in [7].

TABLE 3

Reduction of resistance of earth connection
under impulse conditions

Earthing connection dimensions and arrangement	Depth in earth (m)	3.05			
	Diameter (mm)	10			
	No. of rods and arrangement	1 isolated rod		4 rods at corners of square 3.05m side	
Peak current injected	kA	80		80	
Time to current crest	μs	4		4	
Soil resistivity, ρ, Ω m.		10^2	10^3	10^2	10^3
Resistance at low currents, Ω		30	300	10.5	105
Resistance at current peak, Ω		11.3	54	6.8	37
$\frac{\text{Resistance at current peak}}{\text{Resistance at low currents}}$		0.38	0.18	0.65	0.35

Derived from [28], where values listed were calculated using a dynamic analytical model of soil ionisation under impulse conditions.

3.3.1 *Low Resistivity Areas*

In installations built on ground having a substantial depth of low resistivity soil, an earthing system associated with each structure constructed as described above will enable the target resistances shown in Table 2 to be achieved. Under these conditions, the lightning current either to the structure or to ground near the structure should not cause an excessive voltage rise.

3.3.2 *High resistivity areas*

If normal earthing methods (including methods of extending the earthing given in Appendix 4) are inadequate, either because of overall high ground resistivity, or because of underlying high resistivity material, then it is recommended that the complete installation be earthed by a system of underground conductors, linking all structures in the installation. This recommendation is based on the necessity of avoiding excessive differences in potential between separate parts of the installation. Further details are given in Appendix 5.

3.4 Overall protection of an installation consisting of a number of separate structures

Assuming that each individual structure is protected as far as is technically feasible by the methods given above, it remains to ensure that excessive differences of potential do not occur between different parts of an installation. For example, an installation consisting of two well-separated parts linked by signal and power conductors run in ducting could experience a large potential difference between the parts if one were struck by lightning. To minimise possible resulting damage to equipment, it is recommended that the building or other earths of each part be electrically connected by a low-impedance connection. If the duct is constructed of reinforced concrete, then the steel reinforcing rods should be electrically continuous along the length of the duct, should be bonded transversely at intervals of no more than 15m, and should be securely electrically connected to the local earth at each end.

3.5 The problem of separate building and equipment earths

It may be necessary in some installations to have an equipment earth floating (i.e. electrically isolated) with respect to the building earth. Here the technical and lightning protection requirements conflict to some extent, as resistance to damage by surge voltages is easier to ensure if the equipment earth is connected to the building earth. Problems may be experienced if a voltage impulse injected along signal conductors causes a rise in potential of the equipment earth with respect to incoming a.c. power conductors.

Precautions which should be taken in this situation are as follows:

(i) Ensure that all equipment with a floating earth is protected from direct strokes and that induced surges, and impulse voltages injected at any entry point are diverted to the equipment earth by suitable protective devices.

(ii) Provide protective devices to limit the maximum potential difference between the equipment and building earths. A fairly major problem when this is done is that one can inject lightning currents into mains - it is then necessary to control the potential diffference between the mains and their own earth point.

(iii) Provide floating a.c. mains supply to equipment with floating earth, using transformer windings with adequate insulation.

The manner in which this could be done is illustrated in Fig. 15.

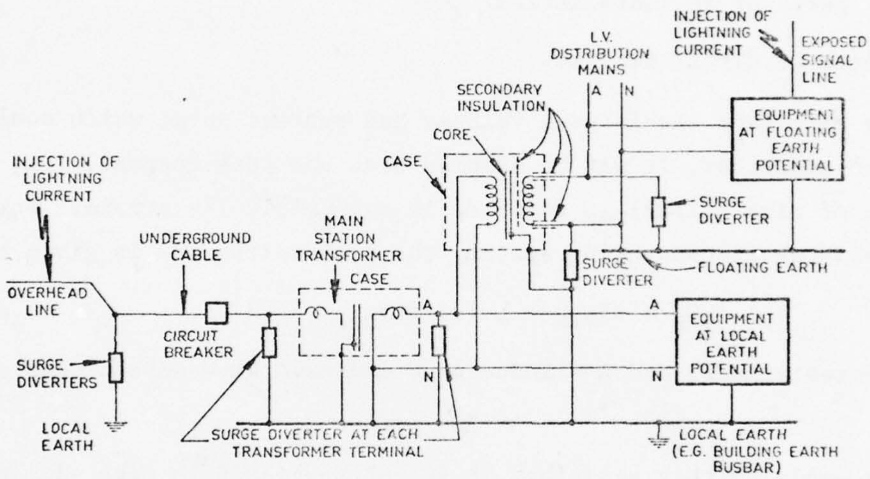


Fig. 15 Protection for equipment with floating earth.

4. ESTIMATING LIGHTNING-CAUSED VOLTAGES AND CURRENTS

As explained in section 2 the lightning stroke is treated as a current source having characteristics given by figures 4 and 8. Observations of lightning currents [29], [30] show that the front of the current waveshape is usually concave, with maximum slope occurring just before the current peak. This combination of high current and simultaneous high rate of rise of current will cause a high voltage in structures, requiring adequate clearances from nearby conductors at earth potential if flashover is to be avoided. Even if there is no flashover substantial induced voltages and currents occur and these may damage equipment in some circumstances. Lightning currents to ground near an installation may cause damaging potential differences between different parts of an installation.

4.1 Effects of direct strikes

To calculate the largest voltage and current surge which could occur in a given conductor, it may be assumed that the peak current, I_{max} and the peak rate of rise $(dI/dt)_{max}$ coincide in any particular stroke. For an electrically short conducting system, the peak voltage V_p is given by

$$V_p = RI_{max} + L\,(dI/dt)_{max} \tag{2}$$

where R = resistance, and L = inductance measured between stricken point and earth.

In applying this equation, it is not realistic to take simultaneously the largest current from line (i) of Fig. 4 and the largest rate of rise of current from line (ii) of Fig. 8, as the former applies to first strokes and the latter to subsequent strokes. A determination should be made as to whether the system involved is more sensitive to peak current or peak rate of rise of current. If the former, damage is likely to be caused by the first return stroke, and appropriate parameters would be

$$\text{SEVERE FIRST STROKE} \begin{cases} I_{max} \approx 80\text{kA to }100\text{kA} \\ (dI/dt)_{max} \approx 30\text{kA}/\mu\text{s} \end{cases}$$

If the system is mainly sensitive to dI/dt, and hence to subsequent strokes the appropriate parameters would be

$$\text{SEVERE SUBSEQUENT STROKE} \begin{cases} I_{max} \approx 40\text{kA} \\ (dI/dt)_{max} \approx 100\text{kA}/\mu\text{s} \end{cases}$$

The method of calculation for typical structures is given in Appendix 6. For an electrically long structure where the travel time of the voltage

waves becomes comparable to the rise time of the injected current pulse, it is necessary to take account of reflected voltage waves as discussed in Appendix 6. For long overhead conductors, the voltages and currents are calculable from the characteristic impedance of the system, taking into account reflected waves where necessary. Some estimated maximum voltages on transmission lines are given in Table 4, based on [18], [31], [32] and [33].

TABLE 4

Maximum voltages on structures directly struck by lightning

Reference	Structure	Maximum Voltage	Notes
Perry (1941) [31]	40kV transmission line tower with 250Ω footing resistance.	8.5MV*	Estimated from 34kA measured stroke current in tower.
Golde (1946) [33]	Transmission line tower, inductance 10μH, tower spacing ∿ 260m. footing res. 20Ω.	20 X Peak current	Calculated (gives 1.6MV for 80kA current).
Sargent and Darveniza (1967) [32]	220kV transmission line tower top.	1.5MV	Calculated from measured 140kA stroke, rise time 4μs.
Wagner and McCann (1950) [18] p. 561	110kV wood pole unshielded transmission line.	5MV	Measured 4 miles (∿ 6 km) from point of strike on line

* Probably overestimated as low-current footing resistance used in calculation. If impulse resistance ≈ 0.2 x low-current value, V_{max} ≈ 1.7MV.

4.2 Induced voltages and currents

A signal conductor near a stricken overhead conductor will have a voltage surge induced in it which can be estimated from the current injected into the stricken conductor and the coupling between the two conductors. A review of induced surges in signal and overhead conductors is given in Appendix 7 showing that an induced current of 8kA is possible. Thus, protection at the terminals of connected equipment is required, and gas arresters are appropriate.

An induced voltage surge will occur in exposed equipment near a

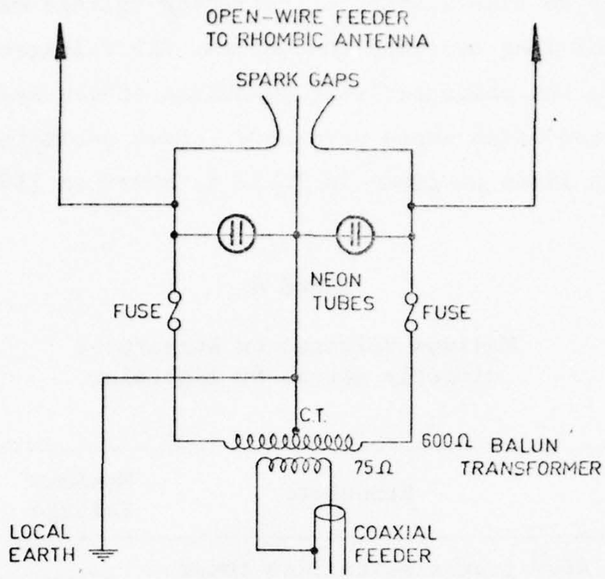


Fig. 16 Existing lightning protection scheme for balun transformer at the base of an RF feeder from a rhombic antenna using spark gaps, fuses, and neon tubes.

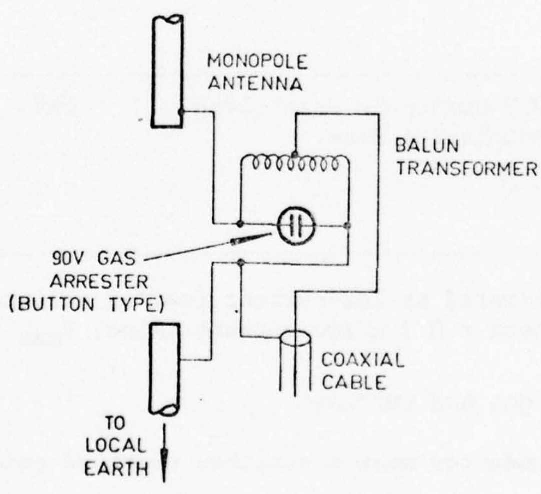


Fig. 17 Existing protection scheme for balun transformer and coaxial cable using 90V gas arrester.

lightning flash to earth. During the progression of the leader discharge towards earth, negative charge is deposited around the leader channel by radial corona currents. When the return stroke commences, a portion of this negative charge is removed. The amount removed is of the order of 1C in a time of about 50μs. The resulting large sudden positive-going change of electric field at the earth's surface induces a large positive voltage surge in any exposed insulated electrode. The sudden increases in current at the beginning of the return stroke causes a rapidly-changing magnetic field near the stroke channel which will induce currents in closed conducting paths. In general, gas arresters will provide adequate primary protection against these surges.

Induced voltage surges in aerials and aerial feeders probably occur in existing installations, either from nearby lightning flashes to ground, or strikes to the mast. It is probable that many of the blown fuses occurring in the protective scheme shown in Fig. 16 are caused thus. Induced surges also undoubtedly occur in the monopole antennas shown in Fig. 17 and are diverted to earth by the gas arrester.

4.3 Effects of earth currents

Any buried conductor such as steel duct or pipe may carry portion of the current spreading from a nearby lightning stroke to ground. In high resistivity soil, most of the lightning current may enter the underground conductor and flow along it, causing a voltage gradient along the conductor. If the conductor is a duct or pipe containing signal or power conductors at the potential of earth remote from the stricken point, large differences of potential can occur. Consequently it is recommended that precautions be taken to drain the lightning current away from the duct or pipe so that the voltage differences are reduced to a tolerable level. It is therefore recommended that the steel reinforcing rods in concrete ducts be connected to earth stakes at approximately 30m intervals. This recommendation is made despite the fact that the earth rods could divert lightning ground currents into the duct metalwork in some circumstances. Best overall protection should be obtained with earth stakes, rather than without them.

Experience with signal conductors in ducts and pipes in a high lightning incidence area shows that sustained insulation breakdown between conductors and pipe or duct is not a common cause of failure. The chief problem is damage to unprotected equipment connected to the signal conductors caused by induced surges. It therefore appears that buried galvanised steel water pipe and reinforced concrete ducts give adequate protection against

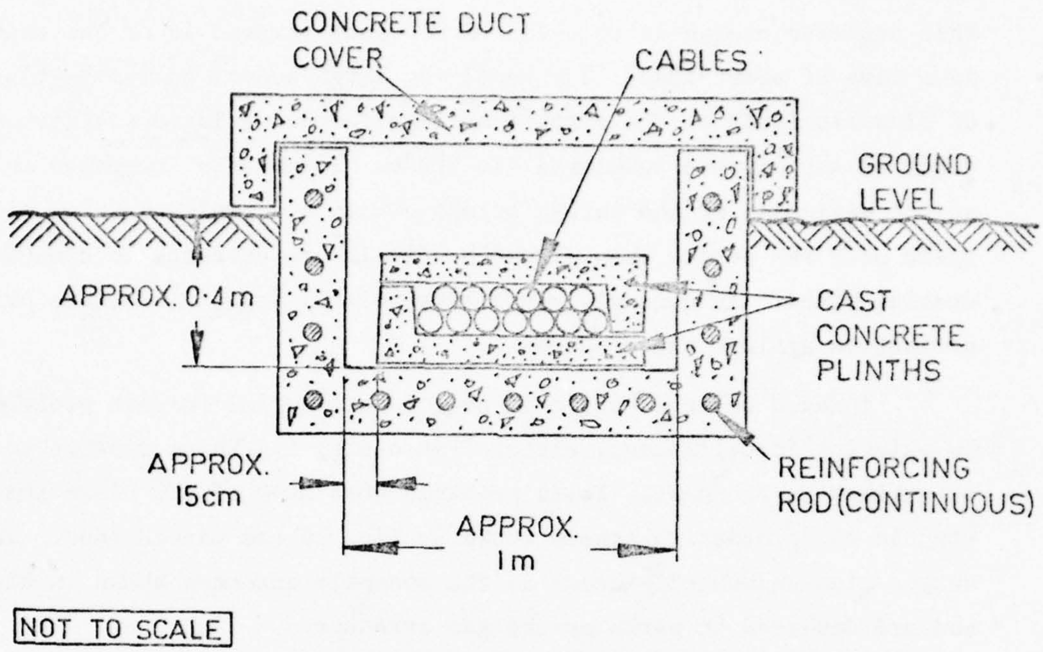


Fig. 18 Use of concrete plinths to support cables in a reinforced concrete duct in an existing installation. The clearance thus maintained between the cables and the duct walls reduces the probability of cable damage by lightning currents in the duct walls.

ground currents from lightning. It is nevertheless recommended that the signal and other conductors run in steel pipe have the highest practicable amount of insulation and separation from the wall of the pipe, and that coaxial cables and other conductors run in ducts be separated from the walls and floor of the duct by suitable spacers, giving a minimum clearance of 10 cm. One arrangement which has given satisfactory service in a high lightning area is shown in Fig. 18, although protection from surges was not the primary intention in this arrangement.

It is necessary that the spacers retain their insulating properties under the damp and unfavourable conditions at the bottom of the duct. Assuming a longitudinal resistance of 1 ohm between points of entry to and departure from the duct of a current of 80kA, an 80kV potential difference may appear between signal conductors at remote earth potential and the duct walls. The spacers should be designed to maintain insulation against voltages of this magnitude. Porcelain post insulators should be considered for the application.

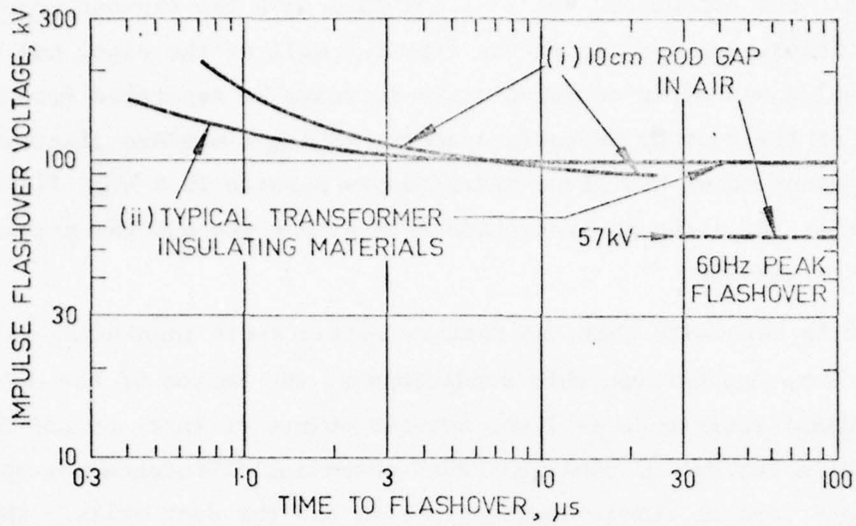


Fig. 19 Impulse flashover voltage versus time to flashover for (i) a 10 cm rod gap in air, (ii) typical transformer insulating materials, adapted from Fig. 8(b), and Fig. 19 of [34].

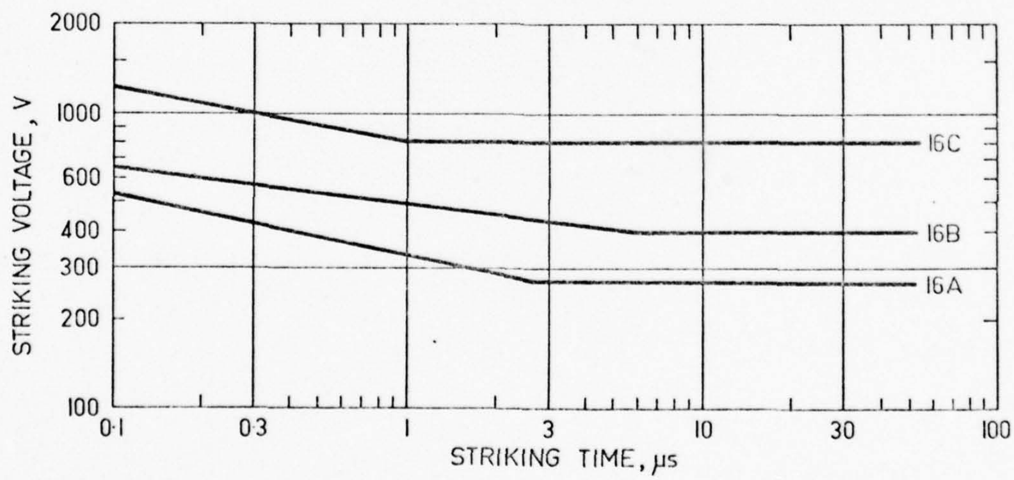


Fig. 20 Breakdown characteristic of three types of three-electrode gas-filled surge arrester. Relation between striking voltage from line to body and striking time.

5. PROTECTIVE DEVICES

5.1 Requirements and applications of devices

Protective devices are used to prevent harmful voltage surges from entering a piece of equipment, without adversely affecting the normal operation of the equipment. As voltage surges may occur at many points in a complete system or installation, and may be caused by switching or other transient conditions as well as lightning, it is recommended that protective devices be installed at certain points in the system.

The function of a protective device connected between a terminal and the earth of a piece of equipment is to present a high impedance up to a certain critical voltage, and a low dynamic impedance above this voltage, so that the energy in incident voltage surges is diverted to earth, and the insulation strength of the equipment is not exceeded.

5.2 Spark gaps

A typical curve relating breakdown voltage to time to breakdown for a 10cm spark gap between rods is shown in Fig. 19. As the voltage impulse resulting from a direct stroke may rise to peak value in 1μs, Fig. 19 shows that a spark gap may fail to protect the insulation of equipment when subjected to steep-fronted voltage impulses. Solid insulation has a smaller time to breakdown than air, as shown in Fig. 19 for typical insulating materials used in transformers [34].

Despite this limitation, spark gaps provide valuable low-cost protection for equipment exposed to direct strike or large induced voltage impulses. Often it is advantageous to place the spark gap some distance from the nearest point at which a direct stroke can contact the conductor to be protected. For example, if a transmitting aerial is connected by an open-wire RF feeder to a balun transformer, and the RF feeder is protected by overhead earth wires so that the nearest point likely to be struck is the aerial itself, then the surge propagated along the RF feeder will be attenuated, and the steepness of the voltage front will be reduced by corona effects and other losses. The spark gap(s) placed at the balun transformer are then more effective in protecting the insulation of the transformer than if the strike were to the RF feeder close to the transformer. On one service transmitting station, the practice is to set the spark gaps at 10% more separation than is necessary to prevent breakdown by the RF voltage.

In applying spark gaps to the protection of equipment connected to receiving aerials, relatively small gaps are needed to protect the equipment.

Small open gaps are unsatisfactory as they may be bridged by moisture, insects, etc. With satisfactory mechanical design, small enclosed spark gaps give useful protection, provided the steepness of the applied voltage wave is not too great.

The protective arrangement shown in Fig. 16 has been found to give protection of the balun transformer and cable, in a high lightning incidence area, replacement of fuses being the only action normally needed to restore the unit following lightning activity. Information derived from [35] on the breakdown characteristics of spark gaps in air is given in Table 5.

TABLE 5

Sphere-gap breakdown voltages

Negative voltage applied to one sphere, other sphere grounded, in air at 20°C, 760 mm Hg pressure. Extracted from [35], Table XV and XVIII.

Breakdown voltages in kV peak

Gap between spheres, cm	Sphere Diameter in cm				
	2	5	10	15	25
0.05	2.8				
0.2	8.0				
0.5	17.1				
1	30.2	32.0	31.6	31.3	31
2		57.4	59.1	59.2	59
3		75.4	84.1	85.5	86
4			105	110	112
5			123	132	137
7			150	169	184
10				209	243
14					304

5.3 Gas discharge devices

The dependence of striking time on striking voltage for a particular gas-filled surge arrester is shown in Fig. 20. Relevant electrical characteristics are listed in Table 6. These protective devices can be used where a very high impedance (in particular, low capacitance) is required during normal operation and the insulation strength at the terminals of the equipment is in the range 100V to 1000V.

TABLE 6 Characteristics of a typical gas-filled surge arrester

Extracted from manufacturer's data sheets for type 16A three-electrode gas-filled surge arrester.

D.C. Striking Voltage	150-350V D.C.
D.C. Arc Voltage	30V max.
Operate Delay Time	1μs max.
Insulation Resistance	10^9 ohm.
Capacitance, end to centre	2.5 pF
Max. Pulse Current (8/20 Waveform)	20,000 A
Max. Striking Voltage for 20 kV/μs applied voltage ramp.	Approx. 1000V

An application of a 90V gas discharge device in protecting the auto-transformer used to match a monopole aerial to coaxial cable is shown in Fig. 17. The short-time current rating of these devices is $\sim 10^4$A, so they are capable of discharging a relatively small lightning current as well as by-passing induced voltage surges to earth. Further, the manufacturer claims that they fail to a short circuit, and therefore should protect the cable even when themselves destroyed by a direct stroke to the monopole.

Gas discharge devices are not self-quenching, so when used in a position where a transmitter (or other source of power) can maintain the discharge current, it is necessary to provide means of disconnecting the power briefly, thus allowing the discharge to cease, and the gas discharge device to revert to the high impedance state.

5.4 Surge diverters

Surge diverters consist of a suitably housed combination of non-linear resistor(s) and spark gap(s); the properties and applications of these devices are described in [36], [37], [38], and [39]. Their primary application is in protection of LV and distribution-voltage-level mains-connected equipment with rating of 240V and above. They may also be useful in other applications requiring discharge of a current surge caused by a direct stroke to a conductor. Some of their characteristics are summarised in Table 7. Surge diverters are able to quench the power-follow current after limiting a voltage surge by discharging current to earth, and in this respect are superior to gaps and gas discharge devices. Surge diverter flashover voltage rises as time to flashover falls, as indicated in Table 7 based on information in [40].

TABLE 7

Characteristics of some surge diverters

Extracted from [36] & [40]

System nominal line-to-line voltage		33kV		11kV		415V	
Rated diverter voltage (connected line to ground) kV rms		30	24	10.5	9	0.5	0.28
Minimum sparkover voltage at power frequency kV rms		45	36	16	13	0.75	0.42
Maximum sparkover voltage for for 1.2/50 impulse wave kV peak		108	87	38	33	2.0	1.5
Maximum front-of-wave impulse sparkover voltage kV peak		125	100	44	38	2.5	2.0
Steepness of wavefront kV/μs		250	200	87	75	10	10
Sparkover voltages at higher dV/dt values (kV peak) (Neg. impulse)	Front Time 0.2 μs 0.1 μs 0.05 μs	*	*	† 41-46 47-54 >58	† 31 37 48	*	*
High impulse current withstand test. kA peak. (4/10 waveshape)	Nominal Impulse Current Rating kA peak 10 5 2.5	 100 65	 100 65	 100 65	 100 65	 65 25	 65 25
Maximum residual voltage when passing rated impulse current kV peak	10 5 2.5	108 108	87 37	38 38	33 33	 2.5 2.5	 2.0 2.0

* Not known.

If the surge diverter is fitted with a pressure relief device, it should conform to the a.c. fault current withstand test in Clause 5.6 of [36].

† These are measured values on particular surge diverters reported in [40].

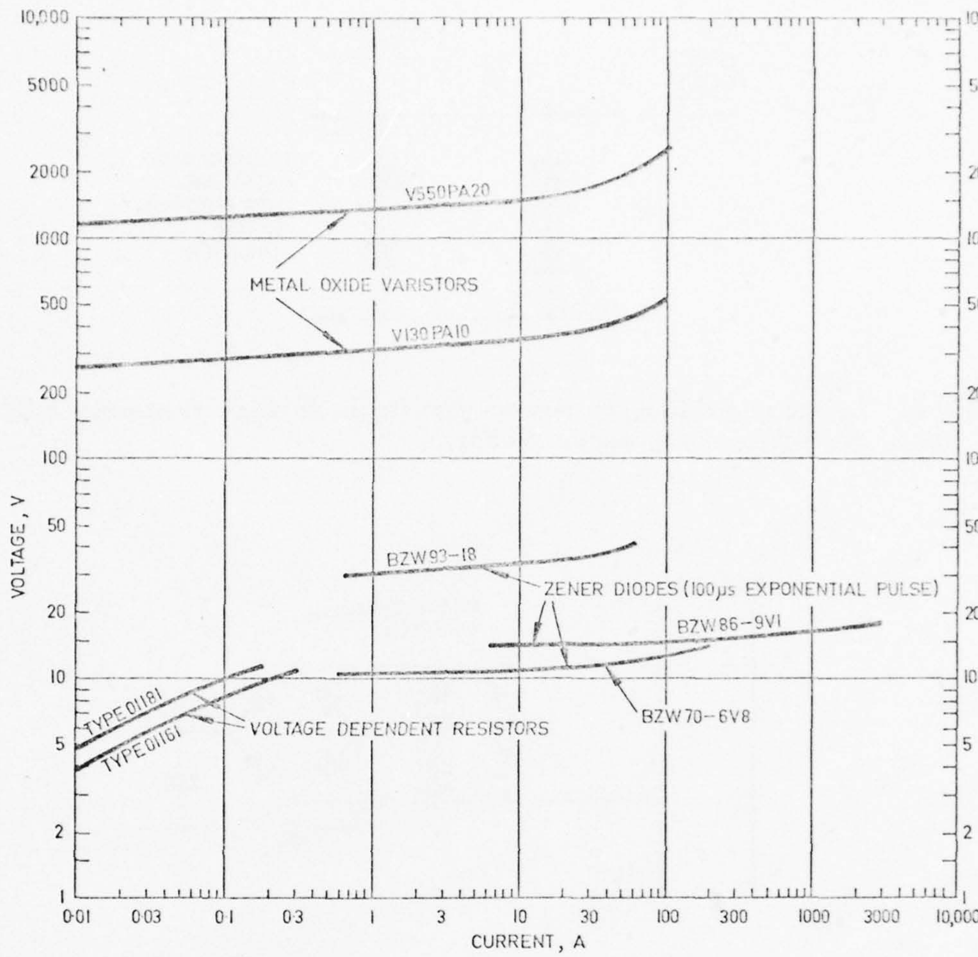


Fig. 21 Voltage versus current characteristics of some metal oxide varistors [41], zener diodes [42, 43] and voltage dependent resistors [44].

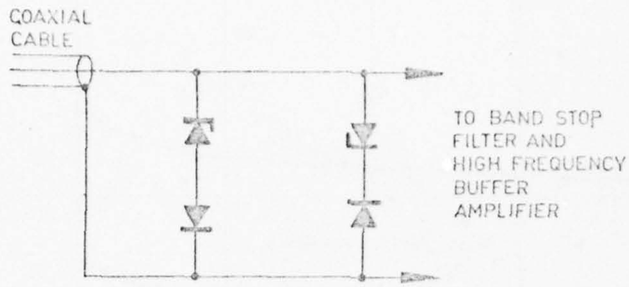


Fig. 22 Existing protective scheme for input to high frequency buffer amplifier using zener diodes.

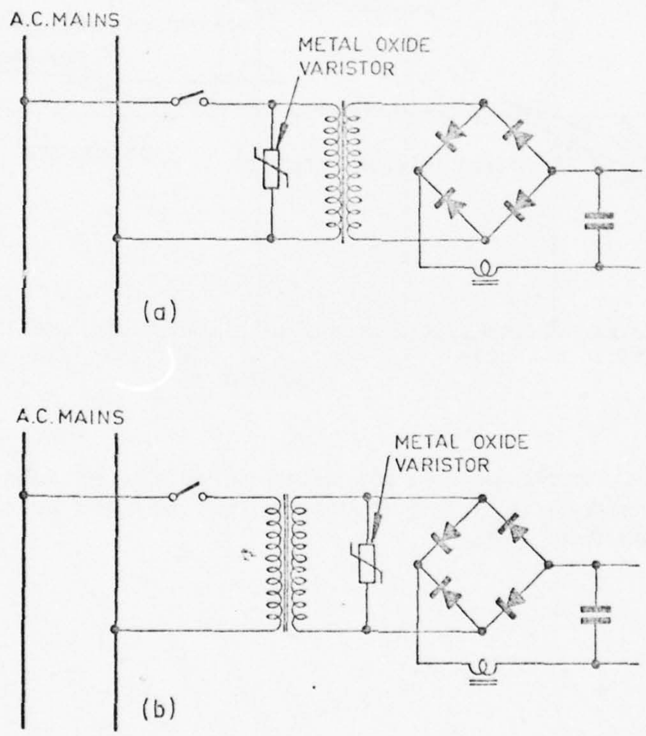


Fig. 23 Application of metal oxide varistor in protecting mains transformer and other parts of equipment.
(a) Protection from transients in a.c. mains
(b) Protection of rectifier from transients caused by internal switching or mains voltage surges.

5.5 Solid-state devices

This group includes metal oxide varistors, non-linear resistors, diodes, zener diodes, and selenium protective devices. Typical current/voltage characteristics are shown in Fig. 21 and electrical and energy-absorbing characteristics are discussed below. Their main applications are in protecting equipment at the power entry point and in protecting signal entry point of equipment where the non-linear impedance presented by the device (including the voltage-dependent capacitance) will not degrade the signal. Refer to manufacturers literature [41] to [44] for further details.

The ideal protective-device current-voltage characteristic has zero current up to a fixed (protective) voltage level and then zero change of voltage with current (i.e. zero dynamic resistance). This would permit selection of the impulse voltage withstand level of the associated equipment just above the fixed protective voltage level. Zener diodes approach this ideal, and are valuable where the maximum prospective surge energy is not high, (not over $\sim$ 3J). An application of zener diodes, used in conjunction with normal diodes, is shown in Fig. 22. Here the energy of the incident surge is limited by the protective devices at the far end of the incoming cable.

An application of metal-oxide varistors in protecting a transformer is shown in Fig. 23. Here the relatively large energy absorbing capability (10 to 40 J) is an advantage, and the relatively low shunt impedance is not a disadvantage.

5.6 Fuses

The relation between current and melting time for one type of fuse is shown in Fig. 24. The relatively long time to melt implies that fuses should not be expected to provide protection against short duration impulses. They are applicable for protection against relatively long-duration overcurrents. If subjected to the full current of a lightning flash, or even a fraction of it, the fuse wire would vaporise, and the current would continue flowing as an arc in the metal vapour. Disconnection of the circuit does not occur until the surge current falls to zero.

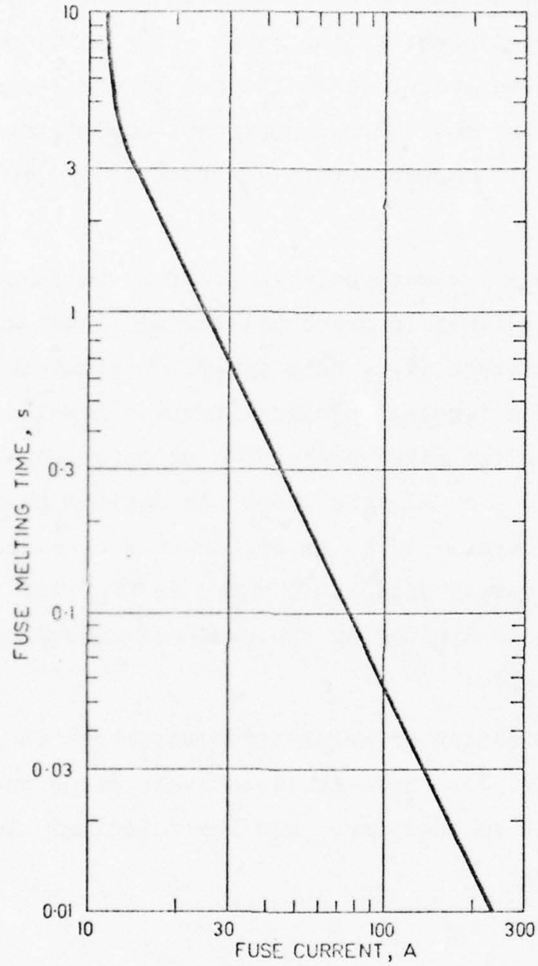


Fig. 24 Current versus melting time curve for one type of fuse Deion type BA-400 rating 7E) Adapted from Section 12-111, of [45].

6. RECOMMENDED SPECIFICATION OF IMPULSE VOLTAGE LEVELS AND PROTECTIVE MEASURES

The preceding sections have defined the main sources of lightning-caused surges which may damage equipment, and shown how the expected currents, voltages, and energy injection may be estimated. Accordingly, the protection of any equipment planned for future installation can be specified in advance, and the required impulse voltage withstand levels can be specified. For existing unprotected equipment, suitable protective measures can be implemented to reduce the probability of future damage.

6.1 Categories of equipment to be protected

Equipments are considered in the following three categories, based on the voltage and power levels at power entry points and signal connection points.

A. POWER DISTRIBUTION EQUIPMENT AND ROTATING PLANT
Distribution - level overhead and underground lines and cables, transformers and rotating plant (motors and generators).

B. MAINS-POWERED LINEAR, DIGITAL, AND ASSOCIATED EQUIPMENT
D.C. power supplies, control system, receivers, amplifiers and buffers (linear), data modems, multiplexers and demultiplexers, digital systems.

C. HIGH-POWER LEVEL HIGH-FREQUENCY EQUIPMENT
RF transmitters.

6.2 Specified impulse levels of power distribution equipment.

In accordance with an agreement between the Defence Services, the Australian Telecommunications Commission, and the power supply authorities [46], all mains power to radio stations must be supplied via underground cable for a specified minimum distance of 1.6km. This practice ensures, inter alia, that lightning - caused mains surges will be limited in amplitude and rise time by the underground cable run. Nevertheless, to minimise possible damage by residual mains surges, or by the effects of ground currents, it is recommended that surge diverters selected in accordance with AS 1307-1974 (see also Table 7) be installed on the HV and LV side of all transformers connected to incoming feeders, being placed as close as possible to the transformer terminals. LV surge diverters should be connected between active terminals and earth at all distribution panels and at all items of plant with a power rating of 10kVA or more unless the entire system is protected from entry of ground currents.

TABLE 8 Recommended insulation levels for power transformers
Extracted from [37].

Insulation level is given as the peak impulse withstand voltage for 1/50μs impulse waveshape applied to one winding with all other windings grounded.

Rating	Exposure to Surges	Nominal rms Voltage Rating of Winding	Insulation Level (Peak Voltages)
10kVA or more	Lines connected to winding exposed to direct strike or induced surge from stricken shield wire. (Suitable surge diverters at winding terminals).	33kV 11kV 1kV or less	200kV 95kV 30kV
	Transformer within fully protected (non exposed) zone, subject only to residual surges passing surge diverters elsewhere in system.	11kV 1kV or less	75kV 30kV
Less than 10kVA	Transformer in fully shielded zone	Less than 1kV	4 x rated rms voltage + 4kV*

* Alternatively, for power frequency insulation test: 2 x Rated rms voltage + 2 kV as rms value of a.c. withstand voltage.

TABLE 9 Recommended insulation levels of power equipment other than transformers

Insulation levels given as the peak impulse withstand voltage (1/50 waveshape) and as the rms power frequency withstand voltage, the voltage being applied to the winding etc. under test with all other parts grounded.

Rating	Exposure to Surges	Nominal rms voltage rating	Insulation Level	
			Impulse kV peak	Power Frequency kV rms
10kVA or more	Connected lines subject to direct strike or induced surge from stricken shield wire. Suitable surge diverters at equipment terminals.	11kV 1kV or less	95 40	48 20
	Equipment within fully protected zone. Supply lines equipped with surge diverters	11kV 1kV or less	75 20 to 30	38 10 to 15
Less than 10kVA	Equipment in fully protected zone	Less than 1kV		2 x rated rms voltage +2kV

Testing of distribution transformers should be in accordance with [37]. Consideration should be given to implementing the recommendations in [47] for modifications to the required type tests on distribution transformers. Recommended insulation levels are listed in Table 8.

For motors, generators, and other equipment not normally subjected to impulse voltage tests, insulation tests at power frequency may be substituted for impulse voltage tests in accordance with Table 9. The impulse or power frequency test voltage is applied between the mains-connected winding as a unit and earth with all other parts of the equipment at earth potential. Surge diverters normally installed between mains terminals and frame (earth) are removed during these tests.

6.3 Protection of signal conductors in exposed positions

It is desirable that signal conductors in exposed situations should be protected from direct lighting strikes. To achieve this, they should be installed in ducting or metal pipe at or below ground level. Alternatively, signal conductors may be run above ground, provided they are entirely within the protective zone of an earthed overhead conductor system. An arrangement of overhead shield wire protection for above-ground signal conductors is shown in Fig. 12. Note that a minimum clearance of 1.5m must be maintained between the overhead earth wire or downleads and the signal conductors to minimise the possibility of flashover from a stricken overhead earth wire to the signal conductor.

Signal conductors in ducting should be run with a minimum clearance of 10 cm from the walls and floor of the duct to minimise the risk of flashover when the duct carries a portion of the lightning current, see Section 4.3. Recommended protective devices and insulation levels at the terminations of signal conductors are dealt with in Section 6.5

6.4 Specified impulse levels and protection at a.c. mains connection point

6.4.1 Equipment in category B

The insulation of the mains-connected winding of transformers in category B equipment should be specified and type-tested in accordance with Table 8. For equipment of less than 10kVA rating supplied from 240V mains, this would mean an insulation level of 5kV r.m.s. at mains frequency.

Type-testing of representative items of equipment should include measurement of the voltage peak on the d.c. side of transformer-rectifier combinations when a specified impulse voltage is superimposed on the normal mains voltage. For 240V mains powered equipment, the recommended test voltage is a 10kV, 2/50μs impulse superimposed on the normal mains voltage,

and applied between active and neutral terminals with surge diverters at the mains terminals removed. The resulting voltage peak on the d.c. side of transformer-rectifier combinations should not exceed the peak inverse voltage rating of the rectifier, or such lower value as may be required to avoid damage to other components on the d.c. side.

In normal service protective devices such as metal oxide varistors should be employed to prevent damage by mains-borne voltage surges, as shown in Fig. 23(a) and (b). They may be positioned to protect transformer insulation, or the rectifier assembly, or both. Capacitor input filters provide surge protection for the associated rectifier assembly and would obviate the need for a metal oxide varistor on the secondary side. A protective device on the primary side could still be desirable to protect the transformer insulation.

Provided the a.c. mains supply and individual items of equipment have been protected as recommended above, and ground currents cannot enter the equipment, damage from mains surges due to lightning is unlikely. Under certain conditions mains surges can be generated within an installation by switching [48] or by other transient conditions. These surges may cause malfunction and insulation breakdown. It is therefore considered good practice to instal the recommended protective devices on all equipment in this category, even where the risk of lightning-caused surges is small.

Problems may arise in applying these protective measures to equipment whose earth floats with respect to the mains earth, to which the mains neutral will normally be connected. In this situation, a floating a.c. supply, obtained from an adequately-insulated transformer winding should be used to power the equipment, and a protective device connected between each a.c. terminal and the equipment earth, see Fig. 15. A protective device is required between the floating earth and local earth to limit the voltage across the transformer insulation.

6.4.2 *Equipment in Category C*

Provided the associated LV mains distribution panels are protected by surge diverters, and the mains connected windings are insulated as recommended in Tables 8 and 9, no further protection should be necessary at mains power connection points. The same considerations should apply to transformer-rectifier combinations, as discussed in 6.4.1 above.

6.5 Specified impulse levels and protection at point of connection of signal conductors to equipment.

6.5.1 *General considerations in protection of signal conductor connection points*

All signal conductors not within a fully shielded zone should be protected from direct strike by one of the methods given above (Sections 3.1 and 4.3). Thus only induced surges should occur in these conductors. The two exceptions considered in this report are the RF feeders from open-wire aerials and monopoles. Gas arresters are already specified for surge current diversion on some monopoles, and similar action is recommended for all open wire aerials. Assuming that this is done, voltages and currents at the receiving end of the RF feeders should be no worse than those caused by the most severe induced surge assumed in this report, provided the feeder itself is protected from direct strike. Thus the forms of protection recommended are applicable to any low power level signal conductor system.

An induced surge in a signal conductor connecting equipment in different parts of an installation can damage the input (or output) circuits of the equipment unless the surge is limited to a level tolerable to the equipment. Where the possibility of induced surges exists, a suitable combination of protective devices should be interposed between the signal conductor and the equipment terminals, either as an addition to existing equipment or as an integral part of the equipment. The protective system should be selected in accordance with the type of signal transmitted, the normal signal voltage amplitude, and the effect of shunt capacitance on the system performance. The types of signal considered are:

(a) signals with voltage excursions of both polarities: low frequency analogue signals, low-level RF signals.

(b) signals with voltage excursions of one polarity: logic-level signals, modulated pulse-train signals.

6.5.2 *Severity of induced surges and basic protection strategy*

It is shown in Appendix 7 that a current surge of the order of 8kA can be induced in signal conductors under certain conditions. The recommended primary protective device is therefore a gas arrester, which should be installed at the point of entry of the signal conductor to the fully shielded zone, e.g. the building, see Fig. 25.

In addition, protective devices at the equipment terminals should be installed to protect against the residual surge resulting from the finite time to breakdown of the gas arrester, from voltages too low to cause the gas arrester to conduct , and from transients resulting from the

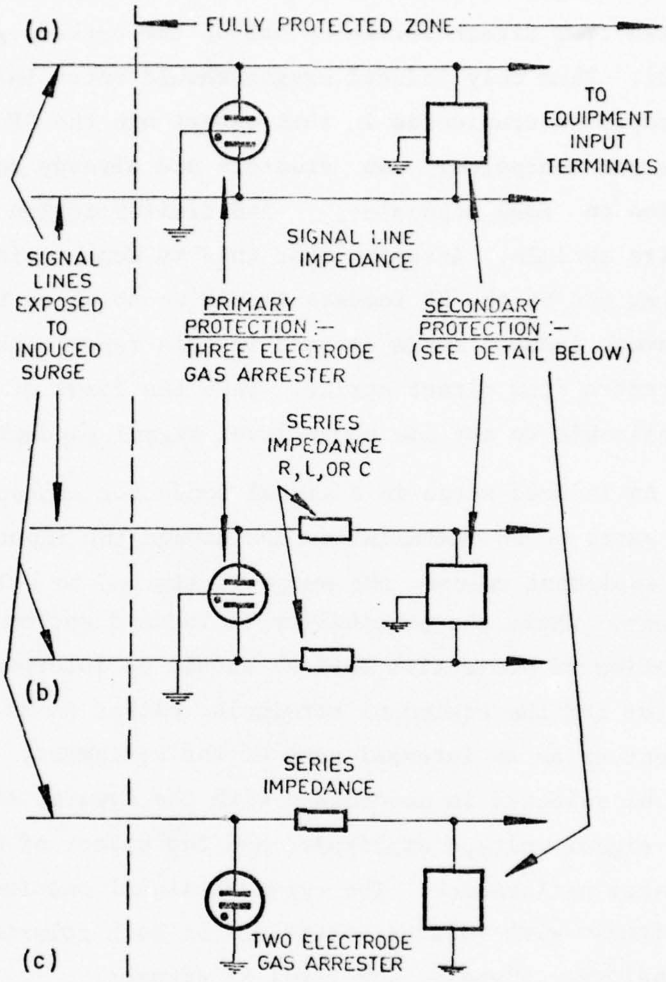


Fig. 25 Illustration of basic strategy for protection of equipment, using a gas arrester as the primary protective device.

breakdown of the gas arrester.

If an appreciable length of signal conductor exists between the entry point to the fully shielded zone and the equipment, the impedance of this section will be sufficient to limit the current to a value within the capability of the secondary protection, Fig. 25(a). Alternatively, additional impedance should be included in series with the signal conductor, Fig. 25(b) and (c).

6.5.3 *Details of primary protection*

For primary protection, a selection is required of the type of gas arrester (two-electrode or three-electrode), and of the d.c. striking voltage rating of the arrester (range approx. 100V to 1000V). Three electrode arresters are recommended where two signal lines are involved, or where the signal line is a coaxial feeder at the point of entry to the receiving equipment, as gaseous breakdown between one line and earth can spread rapidly throughout the tube, and prevent a voltage rise of the other line with respect to earth. Typical gas arrester characteristics are given in Table 6.

6.5.4 *Details of series impedance*

The function of the series impedance is to limit the current entering the secondary protection to a tolerable level. Assuming this current to be 15A, the breakdown voltage of the arrester to be 100V, and the voltage across the secondary protection to be 15V, the series impedance must be about (100-15)/15 ≈ 6 ohm. If this exceeds the series resistance of the signal line between the gas arrester and the equipment, the balance must be provided at the equipment. Considering the case where the entire 6 ohm is provided as a discrete series resistor at the equipment terminals, and a surge just insufficient to fire the arrester occurs, with duration 1ms, the resistor must absorb $85 \times 15 \times 10^{-3} \approx 1.3$J.

If a larger series resistance could be used without degrading system performance, the severity of the current pulse entering the secondary protection would be lessened, simplifying the design of this portion of the protective circuit. Employment of a resistor as the series impedance has the advantage that the unwanted surge energy is dissipated, not stored, and current is limited regardless of the nature of the voltage changes occurring across the gas arrester. Use of series resistance is therefore recommended provided system performance is not degraded to an unacceptable extent. However, for situations where the degradation is unacceptable, a choice must be made of other forms of series impedance. One manufacturer [49] recommends the use of a series capacitor for RF signals and a series inductor for logic signals. Assuming that the impedance of the series capacitor, C, at 1 MHz is

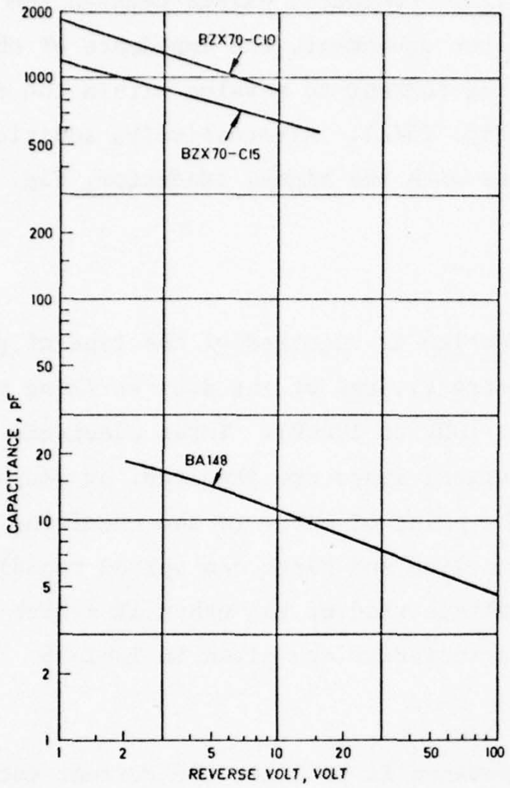


Fig. 26 Variation of capacitance with reverse voltage for silicon diode type BA148 and zener diodes types BZX70-C10 and BZX70-C15. Adapted from manufacturer's data, [42].

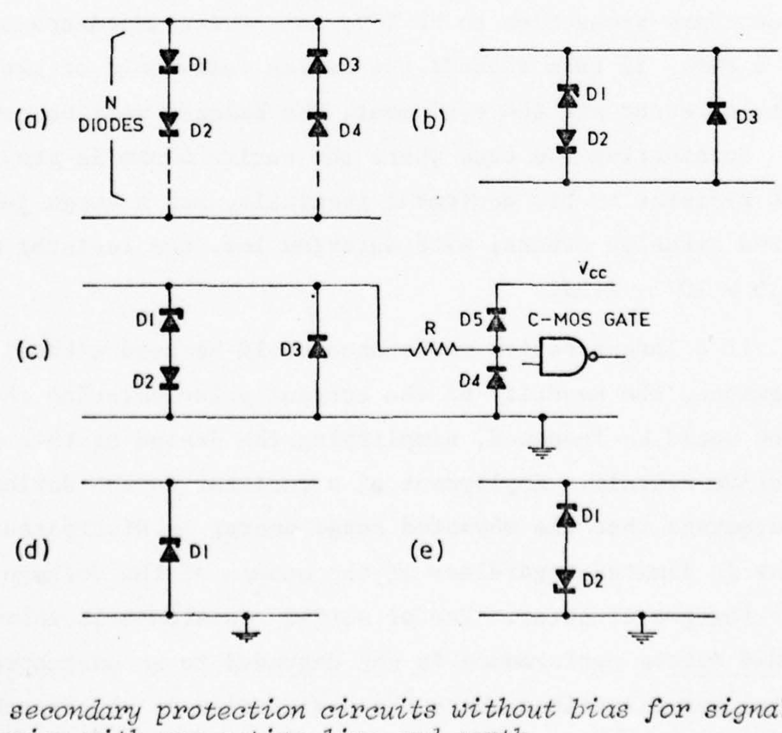


Fig. 27 Various secondary protection circuits without bias for signal transmission with one active line and earth.

not to exceed 1 ohm, its value must be $C = 1/2\pi \times 10^6 \approx 0.2\ \mu F$. Using $(dV/dt)_{max} = I_{max}/C$, with $I_{max} \approx 15A$, $(dV/dt)_{max} \approx 10^8$ V/s, corresponding to the voltage rising from zero to the d.c. striking voltage of the arrester in about 1μs. It is considered likely that this rate of change would be exceeded either on the front of the incoming surge, or at the moment of firing of the arrester, when the voltage across the arrester falls rapidly to zero with the capacitor charged to about 90V. Under these circumstance, the current would be determined by stray circuit inductance, L_s, and the value of C. Assuming at worst that the stored energy $1/2\ CV^2$ is transferred to energy $1/2\ L_sI^2$, then $I \approx V(C/L_s)^{1/2}$. If the largest tolerable value of I is 15A, the smallest allowable $L_s \approx C(V/I)^2 \approx 0.2 \times 10^{-6} \times 6^2 \approx 7\mu H$. If the connections between the gas arrester and the equipment terminals have less inductance, damage to the secondary protection is likely. If a larger RF series impedance can be tolerated resulting in a smaller C, the smallest allowable L_s is correspondingly reduced.

The manufacturer referred to above recommends use of a series inductor, L, as the series impedance element in the protection of logic signal lines. The most severe duty in the system occurs with a long-duration voltage surge just below the d.c. striking voltage of the gas arrester, say 100V. Using $dI/dt = V/L$ or $I = (1/L)\int Vdt$, then $L = \left[\int Vdt\right] / I_{max}$ is the smallest allowable series inductance. If $I_{max} \approx 15A$, $V \approx 10^2$ volt, $dt \approx 10^{-5}$s, then $L \approx 70\mu H$. The manufacturer recommends use of a 100μH choke, having established that pulse voltage rise-times were not significantly degraded by its use. The assumption made above that V = 100 volts for not more than 10μs appears reasonable. If the coupling between the stricken conductor and the signal wire is predominantly capacitive, current injection would occur only during the front of the lightning current waveshape. If the coupling is by mutual inductance, then the analysis of Appendix 7 shows that a current is injected into the signal wire which is similar in waveshape to that of the lightning current. If the induced signal line current $I_s \approx 0.01$ of the lightning current, then a lower limit of dI_s/dt would be $\sim 10^6$ A/s and the voltage across 10^{-4}H wwuld be 100V, i.e. the gas arrester would fire for nearly all induced voltage surges in a time much less than 10μs.

6.5.5 *Details of secondary protection*

In manufacturers' literature and elsewhere [50] many different arrangements of diodes and zener diodes are suggested which will prevent excessive voltage while not interfering with normal operation. It is assumed that the

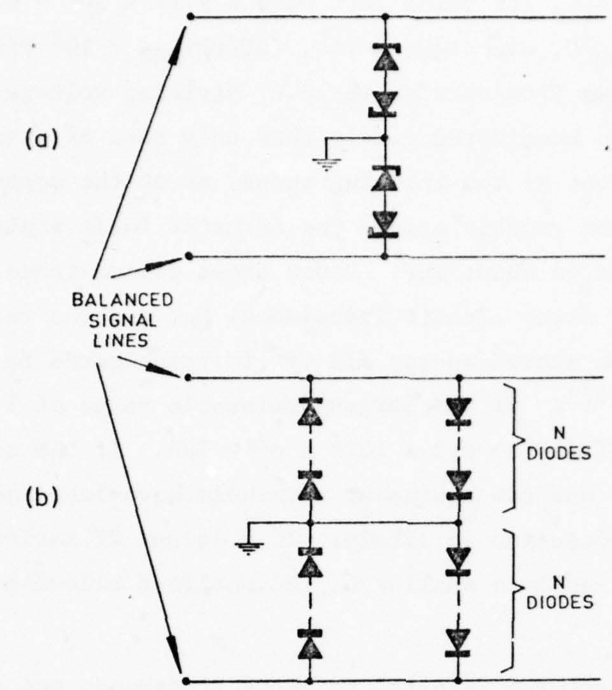


Fig. 28 Unbiassed secondary protection for balanced signal transmission. In (b), N is chosen as discussed in section 6.5.6.

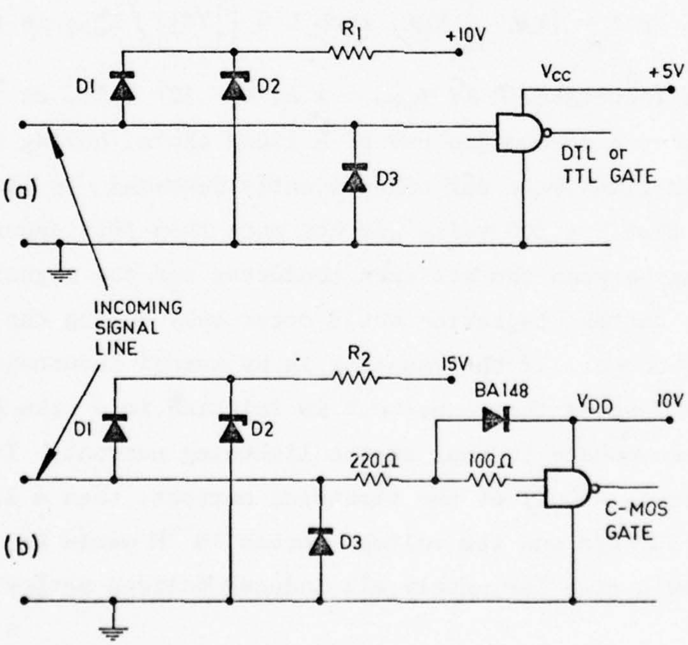


Fig. 29 Two forms of biassed secondary protection for digital signal transmission with signals of only positive polarity. For example, D1 and D3 are silicon diodes type BA148, D2 is zener diode type BZW70-6V8, R_1 = 470Ω.

equipment under consideration here can withstand input voltages in the range 5 to 30V, making gas arresters inapplicable. It is also assumed that non-recurrent surges are limited to ∿ 15A by the series impedance.

Secondary protection can thus be achieved by a combination of diodes and zener diodes [42], [43], arranged to suit the nature of the signal and the permissible voltage swing at the input terminals of the equipment. The capacitance between the signal line and earth caused by the diodes and zener diodes may be an important factor in selecting the appropriate form of secondary protection. A silicon diode such as type BA148 which is capable of carrying a non-repetitive forward current pulse of 15A, has a capacitance C_d at zero applied voltage of ∿ 35pF. C_d falls with increasing reverse voltage, V_R, as shown in Fig. 26.

Diodes capable of carrying a current surge of ∿ 15A generally have an appreciable turn-on time of the order of 1μs when forward biassed. During the turn-on time, a relatively large voltage (10 to 20V) may occur across the diode, which could cause a short-duration voltage pulse at the equipment terminals. It would be necessary to ensure that this pulse could not damage the equipment. Alternatively, if the signal lines and associated circuits prevented large rates of change of voltage from occurring, the finite diode turn-on time would not affect the performance of the protective circuit. Dynamic behaviour of diodes and other semiconductor devices is discussed in Ch. 20 of [51].

Zener diodes with rated zener voltage of about 10V have C_d values from about 100 to 1000pF or more, depending on the current and power dissipation rating. By placing a diode such as BA148 in series with the zener diode, the capacitance is reduced to 30 to 40pF, provided the signal amplitude is small (e.g. tens of mV). This is evidently relied upon in the protective circuit of Fig. 22. In situations where shunt capacitance of 50 to 100pF is unacceptable, the shunt capacitance can be reduced by reverse biassing the diodes as discussed below.

6.5.6 *Unbiassed secondary protection circuits*

Fig. 27(a) shows an arrangement for a low-level analogue signal where the number of diodes in series, N, in each branch is chosen to suit the largest amplitude V_m of the incoming signal. If V_e is the largest forward voltage across a diode at which the forward diode current produces a negligible loading on the signal line, then we require $N \geq V_m/V_e$. Assuming surge current to be limited to 15A, and the forward diode voltage drop to be V_h at this current, the largest voltage surge at the equipment terminals would be $\simeq NV_h$.

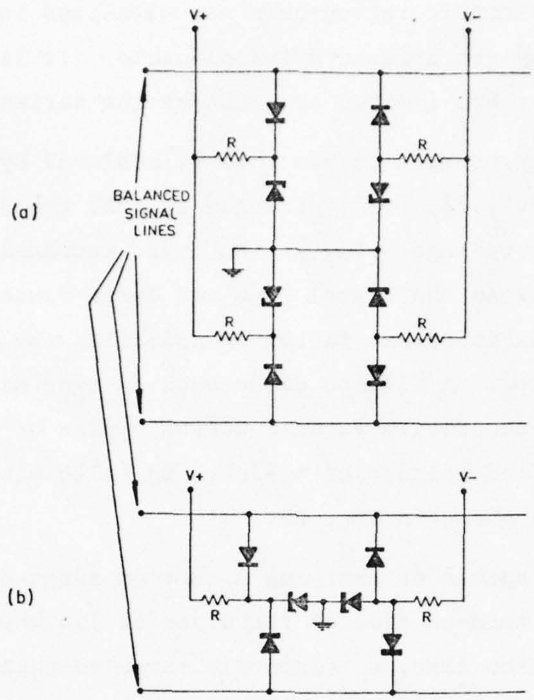


Fig. 30 Two forms of biassed secondary protection for balanced signal transmission.

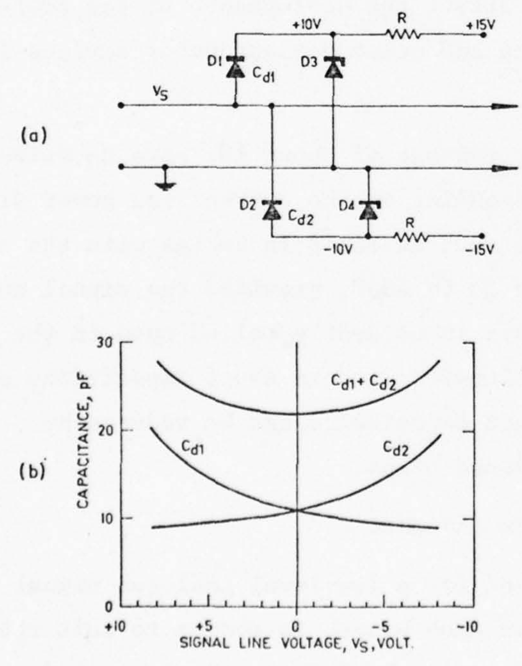


Fig. 31 (a) Secondary protection with bias for signal transmission with one active line and earth, and signal voltages in the range about -6 to +6 volt. For example D1 and D2 are type BA148, D3 and D4 are suitably rated 10V zener diodes, and R ≈ 470Ω.
(b) Combined shunt capacitance, $C_{d1} + C_{d2}$ of reversed biassed diodes D1, D2 as a function of signal voltage, assuming 10V across each zener diode.

Fig. 27(b) shows an arrangement suited to a digital/pulse signal of positive polarity only, zener diode D1 being selected to conduct at a voltage just above the normal signal amplitude. The shunt capacitance will be that of the zener diode, in the range 100 to 1000pF. Assuming the zener diode, to be type BZW70-5V6, the voltage across the device when carrying 15A would be about 9V [42]. Allowing a 1V drop across diode D2 (e.g. type BA148), a voltage pulse of about 10V amplitude occurs when the protection operates, and the logic circuit input would have to be rated to withstand this pulse. Fig. 27(c) shows a similar arrangement with similar characteristics followed by a further stage of surge protection to avoid damage to the input circuit of a C-MOS gate. For example if R = 100Ω, D4 and D5 are silicon diodes such as BA102 [35] the additional time constant introduced would be of the order of 100 ohm x 100pF, which is negligible. The selection of D1 is rendered less critical as the voltage pulse across D1 and D2 may now considerably exceed V_{cc} without causing a gate input voltage greater than V_{cc} plus one diode voltage drop. Fig. 27(d) and (e) consisting of a single zener diode of appropriate rating or a pair of zener diodes back-to-back may be adequate in some situations. These circuits can be adapted for balanced signal lines as shown in Fig. 28.

6.5.7 *Biassed secondary protection circuits*

The shunt capacitance presented by the circuits described above can be considerably reduced by suitable biassing as shown in Fig. 29, 30 and 31. For signals of both polarities on one active line the circuit of Fig. 31(a) is suitable. R is selected to maintain approximately 10V across the zener diodes. The shunt capacitance is the sum of C_{d1} and C_{d2} for diodes D1 and D2 respectively. The manner in which shunt capacitance varies with applied voltage may be estimated graphically as shown in Fig. 31(b). For circuits with one polarity of signal, the circuits of Fig. 29 are suitable, and for balanced signal transmission with both polarities of signal, the circuits of Fig. 30 may be used.

6.5.8 *Specification of insulation levels*

The impulse voltage to be withstood by the equipment input circuit can be calculated from the characteristics of the secondary protection and the maximum current (e.g. 15A) to be absorbed by it. The portion of the signal lines exposed to induced surges should be insulated from earth for a voltage at least 10 times the d.c. striking voltage of the gas arrester used. This will render unlikely insulation breakdown before the gas arrester fires on steep-fronted surges, and allow for some potential drop along the signal line.

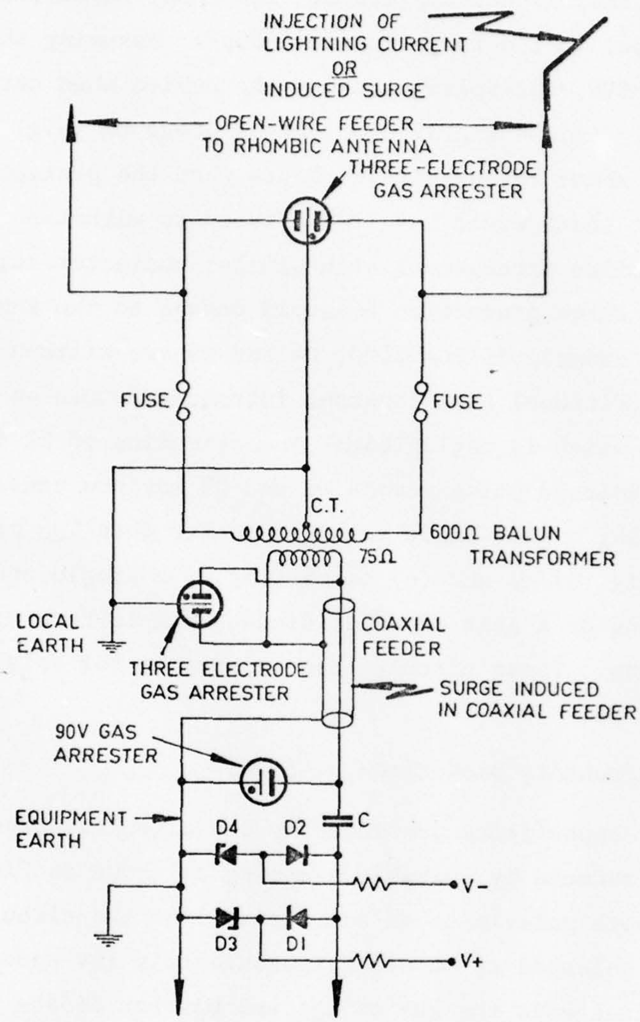


Fig. 32 Illustration of protection against induced surges and direct strike.

The specification of the impulse withstand level of the signal lines and connected equipment may thus be expressed in terms of the expected wave-shape of the induced surge, the breakdown characteristics of the primary protective device (normally a gas arrester), the impedance of the signal conductor, together with any additional impedance, interposed between the gas arrester and the equipment, and the voltage-current characteristic of the secondary protection.

6.5.9 *Example of application of protective devices*

As an example of overall lightning protection strategy, the protection of an RF feeder from a rhombic antenna will be considered, without implying that any particular system is under consideration. The system is shown in Fig. 32. Possible ways a lighting-caused surge could enter this system are as follows:

(a) Direct strike to antenna wire

(b) Strike to supporting mast followed by flashover to antenna wire or open-wire feeder down mast.

(c) Strike to mast causing induced surge in open-wire feeder.

(d) Strike to shield wire protecting coaxial feeder, assumed to be arranged as shown in Fig. 12, causing induced surge in coaxial feeder.

The surge impedance of a mast of the type used to support a rhombic antenna is of the order 100 to 200 ohm during the first microsecond or two of lighting current injection, so the mast top potential can exceed 1MV for typical lightning currents. While coupling between mast, antenna wire, and RF feeder tends to reduce the potential difference between them, it is advisable to provide insulation here for at least 1MV, and more if this is practical.

The recommended protective device to cater for (a), (b), and (c) above is a three electrode gas arrester, as this has low shunt capacitance and high discharge current rating. While a direct strike to the antenna wire will probably destroy the arrester, the balun transformer and coaxial feeder should escape damage.

To cater for (d) above, gas arresters are provided at each end of the coaxial cable as shown, The gas arrester at the 75 ohm side of the balun transformer will protect the inter-winding insulation provided this has a strength of $\sim$ 2kV. The coaxial cable insulation between inner and outer conductors should also have at least this insulation strength.

The arrangement shown in Fig. 12 should provide adequate insulation between the coaxial cable and the supporting and shielding parts.

For protection of the equipment input, a series capacitor C, and biassed secondary protection diodes D1, D2, D3 and D4 are provided. The most severe conditions occur when C is charged to about 80V and the gas arrester fires. It would be necessary to establish that the resulting current pulse through the diodes did not exceed their transient current rating ($\sim$ 15A). If the voltages conditions and diode types were as shown in Fig. 31, the shunt capacitance presented to the RF signal under normal conditions would be about 25pF, and the peak voltage pulse at the equipment terminals would be about 15V lasting at most about 10μs. The equipment input would have to be specified to withstand this pulse.

An alternative method of surge protection in R.F. feeders is under investigation at the University of Queensland. This is based on transformer coupling to provide common-mode surge isolation, saturation of the transformer core being used to limit the amount of surge energy transferred under differential mode conditions. High pass filtering is also incorporated in this protective device to remove the low frequency components of transmitted surges. These techniques could be extended to the device providing the coupling between monopole antennas and coaxial R.F. feeders.

6.6 The transient control level concept

The concept of a transient control level for electronic equipment has recently been presented in [52] and [53]. This is analogous to the BIL (Basic Insulation Level] approach to insulation coordination which has been used successfully for many years in specifying electric power system apparatus. If some measure of agreement can be reached between manufacturers and users of electronic equipment regarding the implementation of the proposals made in [52] and [53] it will greatly simplify the user's task in ensuring protection of his equipment from damage by transients, whether from lightning or any other source.

7. ASSESSMENT OF OVERALL SYSTEM PERFORMANCE

While the recommendations contained in this report should keep the number of lightning-caused faults to an acceptably low level, it must be expected that occasional failures of the protective system will occur. In order to permit assessment of the cause of the failure, with a view to future improvements in protection, it is essential that all relevant information concerning faults which involve the protective system be recorded and reported to Engineering Design Authorities. Details to be reported are listed at Appendix 9.

8. REFERENCES

1. Schonland, B.F.J., The lightning discharge, in Flügge, S., (ed.) Handbuch der Physik, Vol. 22, pp. 576-628, Springer-Verlag, Berlin, 1956.

2. Uman, M.A., Lightning, McGraw Hill, N.Y., 1969.

3. Cianos, N. and E.T. Pierce, A ground-lightning environment for engineering use, Stanford Research Institute, Project 1834, August 1972.

4. Malan, D.J., Physics of lightning, English Universities Press, London, 1964.

5. Journal of the Franklin Institute, Special Issue on Lightning Research, Vol. 283, No. 6, 1967. Articles by several authors.

6. Ashton, H.T., Thunderdays in Australia, Aust.Meteorol. Mag., No. 30, 44-51, Sept. 1960.

7. Australian Standard AS1768-1975 Manual on Lightning Protection. Standards Association of Australia, 1975.

8. Prentice, S.A., and D. Mackerras, Recording range of a lightning flash counter, Proc. Inst. Elec. Eng. (London), 116, (2), 294-302, 1969.

9. Mackerras, D., Lightning occurrence in a subtropical area, Proceedings of the Fifth International Conference on Atmospheric Electricity, (awaiting publication, 1977).

10. Prentice, S.A. and D. Mackerras, The ratio of cloud to cloud-ground lightning flashes in thunderstorms, J. Appl. Meteorol., (awaiting publication, 1977).

11. Bureau of Meteorology, Australia, Lighting flash counter registrations, June, 1976.

12. Prentice, S.A. and D. Mackerras, Lighting data - Australian studies, (in preparation).

13. Berger, K., R.B. Anderson, and H. Kröninger, Parameters of lightning flashes, Electra, No. 41, pp. 23-37, July 1975.

14. Tsurumi, S., K. Kinoshita, and G. Ikeda, Some results on lighting stroke measurements in Japan, in Coroniti, S.C. and Hughes, J., (ed.) Planetary Electrodynamics, Vol. 1, pp. 483-488, Gordon and Breach, N.Y. 1969.

15. Lewis, W.W. and C.M. Foust, Lightning investigation on transmission lines, Trans. A.I.E.E., 64, 107-115, 1945.

16. Hagenguth, J.H. and J.G. Anderson, Lightning to the Empire State Building, Part III, Trans. A.I.E.E., 71, 641-649, 1952.

17. A.I.E.E. Committee Report, A method of estimating lighting performance of transmission lines, Trans. A.I.E.E., 69, 1187-1196, 1950.

18. Wagner, C.F. and G.D. McCann, Lightning phenomena, in Electrical Transmission and Distribution Reference Book, Westinghouse Electric Corporation, Fourth ed. pp. 542-577, 1950.

19. Hylten-Cavallius, N. and A. Stromberg, Field measurements of lightning currents, Elteknik, 2, 109-113, 1959.

20. Popolansky, F., Study of lightning strokes to high objects in Czechoslovakia, Electrotech. Obzor., 53, (5), 242-246, 1964. Reference translation/IB2291 of Electrical Research Association.

21. Popolansky, F., Frequency distribution of amplitudes of lightning currents, Electra, No. 22/24, 1972.

22. Szpor, S., Comparison of Polish versus American lightning records, Trans. A.I.E.E., PAS-88, 646-652, 1969.

23. Sargent, M.A., The frequency distribution of current magnitudes of ligtning strokes to tall structures, Trans. I.E.E.E., PAS-91, (5), 2224-2229, 1972.

24. Beck, E., Lightning strokes prefer tall structures, Westinghouse Engineer, 9, 124-128, July 1969.

25. Wagner, C.F., G.D. McCann, and C.M. Lear, Shielding of substations, Trans. A.I.E.E., 61, (2), 96-100, 1942.

26. Trueblood, H.M. and E.D. Sunde, Lightning current observations in buried cable, Bell System Technical Journal, 28, 278-302, 1949.

27. Bodle, D.W., Crushing of buried cable by cold lightning, Bell Lab. Record, 34, (3), March 1956.

28. Liew Ah Choy and M. Darveniza, Dynamic model of impulse characteristics of concentrated earths, Proc. I.E.E., 121, (2), 123-135, 1974.

29. Berger, K. and E. Vogelsanger, Messungen und Resultate der Blitzforschung der Jahre, 1955 ... 1963, auf dem Monte San Salvatore, Bull. S.E.V., 56, 2-22, 1965.

30. Garbagnati, E., E. Guidice, G.B. LoPiparo, and U. Magnagnoli, Survey of the characteristics of lightning stroke currents in Italy, results obtained in the years from 1970 to 1973. Report by Ente National per l'Energia Elettrica, Milan, Italy, 1974.

31. Perry, F.R., The measurement of lighting voltages and currents in South Africa and Nigeria, 1935 to 1937, J.I.E.E., 88 II, 69-87, 1941.

32. Sargent, M.A. and M. Darveniza, The calculation of double circuit outage rate of transmission lines, Trans. I.E.E.E., PAS-86, (6), 665-678, 1967.

33. Golde, R.H., Lightning currents and potentials on overhead transmission lines, J.I.E.E., 93 II, (36), 559-569, 1946.

34. Monteith, A.C. and H.R. Vaughan, Insulation Coordination, in the Electrical Transmission and Distribution Reference Book, Westinghouse Electric Corporation, Fourth ed., pp. 610-642, 1950.

35. Craggs, J.D., and J.M. Meek, High voltage laboratory technique, Butterworths Scientific Publications, London, 1954.

36. Australian Standard Specification AS 1307-1974, Surge Diverters Non-Linear Resistor Type, Standards Association of Australia, 1974.

37. Australian Standard Specification AS C61-1970, Power Transformers, Standards Association of Australia, 1970.

38. Beck, E., Lightning protection for electric systems, McGraw-Hill, N.Y., First ed., 1954.

39. Monteith, A.C., Line design based upon direct strokes, in the Electrical Transmission and Distribution Reference Book, Westinghouse Electric Corporation, Fourth ed., pp. 578-609, 1960.

40. Parnell, T.M., M. Darveniza and I.K. Vosper, The testing of surge diverters with steep fronted impulse voltage waves, Preprint of paper issued by Inst. of Engineers, Aust., Queensland Division, April 1976.

41. GE-MOV Metal Oxide Varistors 130-575 volt rms a.c. 170-780 volts d.c. Device information supplied by General Electric Co., U.S.A. 1973.

42. Philips Data Handbook, Semiconductors and integrated circuits, Part 1a, June 1974.

43. Philips Data Handbook, Semiconductors and integrated circuits, Part 1b, October 1975.

44. Philips Data Handbook, Components and Materials, Part 2a, Sept. 1974.

45. Knowlton, A.E. (ed.), Standard Handbook for Electrical Engineers, McGraw-Hill, N.Y., Ninth edition, 1957.

46. Australian Inter-Department Telecommunication Advisory Committee Code of Practice for the Installation of Power, Telephone and Remote Control Cables near Ground Radio Stations.

47. Carter, J.F., M. Darveniza, N. Logothetis and T.M. Parnell, Investigation of selected high voltage tests on the windings of 11kV distribution transformers, Elect. Eng. Trans. I.E.Aust., EE12, (2), 89-97, 1976.

48. Kay, D., Transient suppression - don't make the cure worse than the disease, Machine Design, Feb. 1975

49. Mayhew, R.A. and J.R. Eastwell, Investigation into lightning protection of the DF-1 system, Report No. 4390/75/2, The Plessey Company Ltd., 1975.

50. Knox, K.A.T., Semiconductor devices in hostile electrical environments, Electronics and Power, 19, (22), 557-560, Dec. 1973.

51. Millman, J., and H. Taub., Pulse, digital, and switching waveforms, McGraw-Hill, N.Y., 1965.

52. Fischer, F.A., and F.D. Martzloff, Transient control levels - a proposal for insulation coordination in low-voltage systems, I.E.E. Trans. on P.A.S., PAS-95, (1), 120-129, 1976.

53. Crouch, K.E., F.A. Fisher and F.D. Martzloff, Transient control levels - a better way to voltage ratings in power converter applications, To be presented at I.E.E.E. Meeting in 1977.

54. Golde, R.H., Lightning Protection, London, Arnold, 1973.

55. M.I.T. Staff, Magnetic circuits and transformers, N.Y., Wiley, 1943.

56. C.C.I.T.T., Earthing of Telecommunication Installations, To be published by International Telecommunication Union.

57. Sunde, E.D., Earth conduction effects in transmission systems, N.Y., D. van Nostrand, 1949.

58. Aust. Telecommunication Commission, Earths and Earthing Systems, Cable Protection Section, Queensland, Book 9, Issue 2, February 1975.

59. Code of Practice of Protective Earthing - 1965. Issued by the Electricity Authority of New South Wales, Australia.

60. Department of Transport, Aust., Lightning protection of ground equipment with particular reference to Department of Transport remote electronic equipment. Internal departmental report prepared by N. Moore.

61. Jordan, C.A., Lightning computation for transmission lines with overhead ground wires, Gen. Elec. Rev., 37, pp. 130-137, 180-185, 243-250, 1934.

62. Bewley, L.V., Travelling waves on transmission systems, 2nd ed., N.Y., Dover, 1951.

63. Wagner, C.F., and A.R. Hileman, A new approach to the calculation of the lightning performance of transmission lines III - a simplified method: stroke to tower, Trans. A.I.E.E. on P.A.S., 79, 589-603, 1960.

64. Sargent, M.A., and M. Darveniza, Tower surge impedance, I.E.E.E. Trans. on P.A.S., PAS-88, (5), 680-687, 1969.

65. Darveniza, M., Calculation of transmission line transients, Ch. P6 in Power System Engineering, ed. S.A. Prentice and T.M. Parnell, Department of Electrical Engineering, University of Queensland, 1976.

66. Carter, G.W., The electromagnetic field in its engineering aspects, London, Longmans, Green & Co., 1954.

67. C.C.I.T.T., The protection of telecommunication lines and equipment against lightning discharges. Published by the International Telecommunication Union, 1974.

68. P.M.G. Department, Aust. (now Aust. Telecommunication Commission) Protection of telecommunication circuits against induced voltages from lightning and electric power lines, External Plant Information Bulletin No. 11, Engineering Division, P.M.G. Department, Aust., 1958.

69. O'Callaghan, P.M., Lighting performance of telecommunication cable, Bachelor of Engineering Thesis, University of Queensland, 1976.

9. GLOSSARY

Thunderstorm-day or thunder-day : Day with thunder heard at one location.

Lightning flash : An electrical discharge in the atmosphere usually occurring between electrically charged zones in a cumulonimbus cloud or between one of these zones and earth. The discharge typically has a length of the order of kilometres and a duration of the order of a second.

Lightning discharge : Synonymous with lightning flash.

Ground flash : A lightning flash between a charged zone in a cloud and earth. (Sometimes referred to as a cloud-ground flash or a lightning flash to ground).

Cloud flash : A lightning flash which does not strike the earth. (Sometimes referred to as a cloud-cloud flash or sky-flash).

Intra-cloud flash : A could flash within one thundercloud.

Inter-cloud flash : A cloud flash between two thunderclouds, or at least between two distinct and separate cells within a bank of clouds.

Lightning stroke : A partial discharge during a ground flash, having a duration of the order of a millisecond and involving one high-current impulse in the discharge channel between cloud to earth.

Multiple-stroke ground flash : A ground flash comprising more than one lightning stroke.

Interstroke interval.: Time interval between successive strokes in a multiple-stroke flash.

Sign of electric field change : The electric field change resulting from a ground flash is defined as positive when this change is caused by a transfer of negative charge from cloud to ground.

Ground flash density (N_g) : The number of ground flashes per unit time and per unit area of the earth's surface.

Cloud flash density (N_c) : The number of cloud flashes per unit time and per unit area of the earth's surface.

Total flash density : $N_c + N_g$.

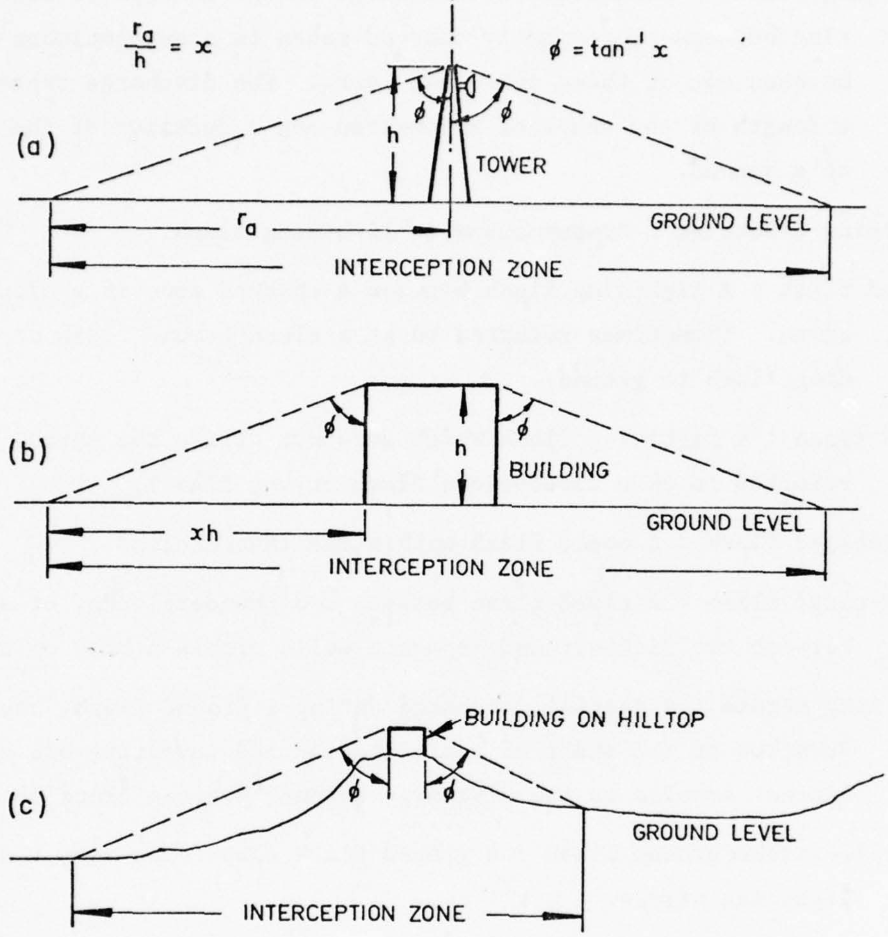


Fig. A1.1 Illustration of the zone over which an elevated structure intercepts lightning (interception zone).

APPENDIX 1

ESTIMATION OF EFFECTIVE AREA OF AN ELEVATED INSTALLATION OR STRUCTURE FOR INTERCEPTING LIGHTNING

As shown in section 2.3 and Fig. 5, any elevated object tends to divert towards itself the down-coming lightning leader, and is therefore struck more often than its plan area would indicate. If the object is h metres high, it intercepts lightning strikes over a radius r_a. Letting $x = r_a/h$, we see from the broken lines in Fig. 5 that the ratio x varies to some extent with h, and has a value of about 3 to 5 or more for objects up to 100 m high, according to [3].

It appears reasonable to extend the idea of the interception zone of an isolated tower to a situation involving a tall building of relatively large plan area, or a building on a hilltop, as shown in Fig. A1.1. The technique illustrated enables the dimensions of the interception zone to be obtained by calculation or scale drawing, and hence the effective area, A_{eff} for interception of lightning to be calculated. Then the expected number of lightning strikes per year is simply $N_g A_{eff}$. For conservative estimates of this quantity, it is recommended that the value $x = 5$ be used, corresponding to $\phi = \tan^{-1} 5 = 79°$.

It should be noted that the notion of an interception zone has only a statistical validity, as some high-current flashes outside the zone may strike the object and some low-current flashes may strike the ground within the interception zone. Thus the interception zone should not be interpreted as a protected zone. For satisfactory protection, much smaller angles are required (or even negative angles) as shown in Fig. 9.

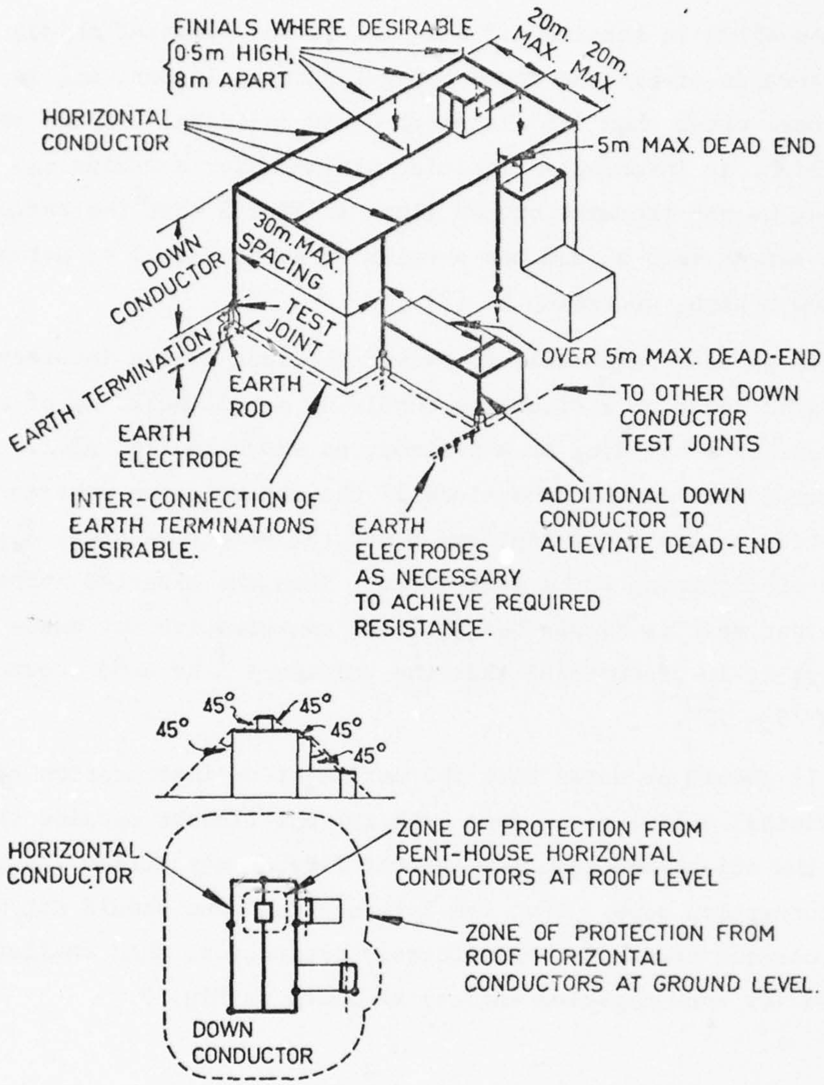


Fig. A2.1 Detail of air terminations, downleads and earthing system for lighting protection of a building. Adapted from Fig. 5 of [7].

APPENDIX 2

LIGHTNING PROTECTION OF BUILDINGS, INCLUDING CONDUCTOR TYPES

A general account of lightning protection of buildings is given by R.H. Golde [54] and specific recommendations for Australian conditions are contained in Australian Standard AS1768 - 1975 [7]. A brief account is given here of the main recommendations in [7] which should be applied where the cheap and effective, but aesthetically less pleasing protective system suggesting in section 3.1 and Fig. 10, cannot be employed.

For buildings of simple shape such as the one shown in Fig. 11, the basic principle is to place earthed conductors in positions where they are likely to launch a "successful" return streamer, i.e. one which diverts the lightning path to the conductor. Such a conductor is termed an air termination. They should be placed along all upper edges of the building as shown in Fig. 11 and Fig. A2.1. Additional horizontal conductors should be placed acrosss the roof so that no part of the roof is more than 10m from a conductor. Down conductors linking the air terminations to the earthing system should be placed at intervals not greater than 30m around the building. Where different portions of a building have different heights, as in Fig. A2.1, the additional air terminations required should be provided with an additional downlead, unless the overhang is less than 5 m (see Fig. A2.1).

The materials recommended for both air terminations and downleads are copper and aluminium. The minimum dimensions are as follows.

Strip : 20 mm x 3 mm
Rod : 10 mm dia.
Stranded conductors: 35 mm^2

Where aluminium is selected, copper or copper-covered or copper alloy fittings should not be used. Fastenings and jointing should ensure low resistance electrical joints, freedom from corrosion troubles, and mechanical soundness.

APPENDIX 3

CALCULATION OF HEATING EFFECT OF LIGHTNING CURRENTS

This appendix is concerned chiefly with calculating the transient heating of overhead ground wires used to intercept and divert to earth lightning stroke currents. Some references to observations on the heating of thin metal sheets are also given.

It will be assumed that the lightning current, I, flows through a metal conductor of uniform cross section area A_w, length L, and that the metal has density D, resistivity at ambient temperature ($\sim 20°C$) ρ_0, thermal coefficient of resistivity α, and specific heat S. The temperature rise above ambient is θ(°C). It will be assumed that the energy injection occurs in about 1 s, so heat loss by radiation etc. is negligible. Thus the energy injected is entirely stored as thermal energy in the conductor.

The energy injection can be measured in terms of the quantity $g = \int I^2 dt$, referred to in [3] as the action integral, where it is stated that for 50% of flashes g exceeds $4 \times 10^4 A^2 s$, and for 2% of flashes g exceeds $10^6 A^2 s$.

The problem is complicated by the fact that several of the variables involved are functions of temperature, but for the present calculation it will be assumed that the dominant effect is change of resistivity with temperature, and that this can be allowed for by assuming α constant, so

$$\rho = \rho_0(1 + \alpha\theta) \qquad (A3.1)$$

gives the resistivity at any temperature rise, θ.

Following the treatment given in [55] p. 253, consider an incremental temperature rise $d\theta$ caused by an increment dg in g, during time dt. The following relations hold.

$$\text{Mass of wire} = D A_w L \qquad (A3.2)$$

$$\text{Resistance of wire} = \rho L/A_w$$

$$= \rho_0(1 + \alpha\theta)L/A_w \qquad (A3.3)$$

$$\text{Energy injection} = I^2 dt \rho_0(1 + \alpha\theta)L/A_w \qquad (A3.4)$$

This energy is stored as an incremental increase in thermal energy.

As $$I^2 dt = dg, \qquad (A3.5)$$

we have $$D A_w L\, S\, d\theta = dg\rho_0(1 + \alpha\theta)L/A_w \,, \qquad (A3.6)$$

So $$\frac{d\theta}{1 + \alpha\theta} = \frac{dg\, \rho_0}{A_w^2\, D\, S} \qquad (A3.7)$$

On integrating this, and applying the condition $\theta = 0$ when $g = 0$, we obtain

$$\frac{1}{\alpha} \log_e(1 + \alpha\theta) = \frac{g}{A_w^2} \cdot \frac{\rho_0}{DS}$$

or $$\log_e(1 + \alpha\theta) \doteq \frac{g}{A_w^2} \frac{\rho_0\alpha}{DS}, \qquad (A3.8)$$

so $$\theta = \frac{1}{\alpha}\left[\exp\left(\frac{\rho_0\alpha}{DS}\right)\left(\frac{g}{A_w^2}\right) - 1\right] \qquad (A3.9)$$

The materials most likely to be used in this application are copper, galvanised steel, and aluminium. Approximate values of D, S, ρ_0, α, and $\rho_0\alpha/DS$ for these materials are listed in Table A3.1.

TABLE A3.1

Material	D $g.cm^{-3}$	S $Jg^{-1}{}^\circ C^{-1}$	ρ_0 ohm cm	α $^\circ C^{-1}$	$\rho_0\alpha/DS$ ohm cm^4J^{-1}
Copper	8.9	0.385	1.77×10^{-6}	0.004	2.07×10^{-9}
Galv. steel	7.8	0.460	11×10^{-6}	0.004	12.27×10^{-9}
Aluminium	2.7	0.945	2.83×10^{-6}	0.004	4.44×10^{-9}

Using the constants in Table A3.1, the relation between θ and g/A_w^2 may be plotted for each material, as in Fig. A3.1, where g is in A^2s, and A_w is in cm^2. These curves may be used to determine minimum values of A_w for given maximum temperature rise and assumed value of g. For example, if θ_{max} = 500°C, g = 10^6A^2s corresponding to a severe lightning flash, the minimum values of A_w are as follows

	Minimum A_w cm^2	Diameter of round conductor (cm)
Copper	0.043	0.23
Galv. Steel	0.105	0.37
Aluminium	0.063	0.28

Thus conductors of practical size have a considerable safety margin against thermal damage, even allowing for some additional heat injection from the lightning channel near the point of strike. That the above conductor sizes are conservative can be inferred from the observation in [56] that only one out of 100 lightning strikes to telecommunication lines causes melting and breaking of the wires which have a cross sectional area of about 10 mm^2. It appears that the localised melting at the point of strike is caused more by heat transferred from the lightning channel than by I^2R heating.

Observations of the puncture of thin metal sheets by lightning are reviewed in [54]. The size of the hole made in the sheet appears to be related to the charge delivered, and the thickness of the metal sheet. For example, delivery of a charge of 100C, corresponding to a fairly severe lightning flash, was observed to cause holes as follows.

Material	Thickness (mm)	Approx. size of hole (mm^2)
Stainless steel	0.25	300
Copper	0.51	150
Aluminium	1.3	60
Aluminium	2.54	20

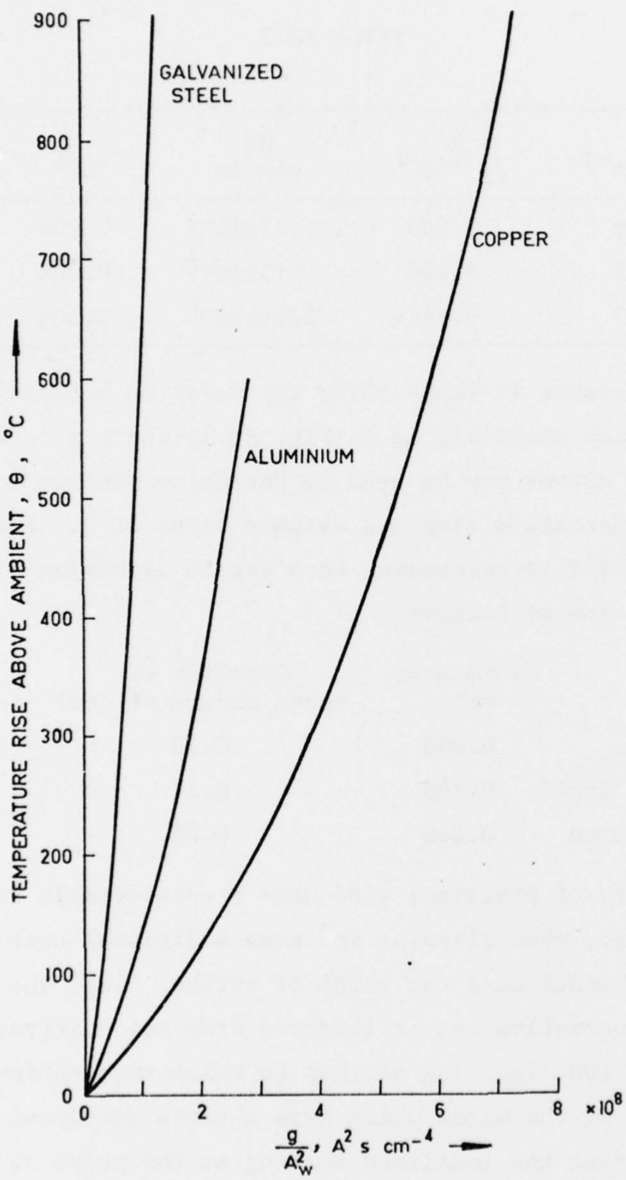


Fig. A3.1 Transient heating curves for copper, aluminium, and galvanised steel conductors carrying lightning current.

APPENDIX 4

RECOMMENDED EARTHING FOR BUILDINGS AND TOWERS AND MEASUREMENT OF EARTH RESISTANCE

A general account of earthing for the purpose of lightning protection is given in [54] and [57] and detailed recommendations are given in [56], [58], and [59]. In this appendix a summary is given of some of the recommendations contained in these references.

The general layout of the earthing system suitable for a building is shown in Fig. 11 and in Fig. A2.1. Individual earthing rods are driven to a depth of one or two metres and may be copper, aluminium, or galvanised steel, depending on local experience with corrosion problems. An isolated round rod of radius a(m) driven a distance ℓ(m) into ground of uniform resistivity ρ(Ωm) has a resistance R(Ω) given, according to [54] by

$$R = \frac{\rho}{2\pi\ell}\left(\log_e \frac{4\ell}{a} - 1\right)\Omega \qquad \text{(A4.1)}$$

Thus the variation of earth resistance with the depth to which the rod is driven can be plotted as in Fig. A4.1, where the curve is drawn for a rod or pipe 25mm outside diameter. The vertical ordinate for a given ℓ is multiplied by the resistivity ρ, to obtain R. The curve shows that R decreases quite slowly once a depth of 1 to 2m is reached, so it is more profitable to drive, say, four rods to a depth of 1m than one rod to a depth of 4m, provided the four rods are well spaced (e.g. 3m or more apart). An exception to this general rule exists where high resistivity surface soil overlays low resistivity soil. It may then be essential to drive rods to considerable depth to achieve a required earth resistance.

The building earth would normally have earth rods at each corner of the building, and sufficient additional rods to achieve the target earth resistance. In high resistivity soil where the required number of rods becomes excessive, i.e. the rods have to be placed very close together, it would be no longer valid to combine their resistances as independent parallel paths to earth. It would then become necessary to extend the earthing system outward from the building, as suggested in Fig. A2.1.

It may be found that a buried strip electrode becomes more economical than a number of driven rods. The earth resistance of a strip electrode of radius a(m), length ℓ(m), buried at depth d(m) is soil of resistivity ρ(Ωm) is given according to [54] by

$$R = \frac{\rho}{\pi\ell}\left(\log_e \frac{2\ell}{\sqrt{ad}} - 1\right)\Omega \qquad \text{(A4.2)}$$

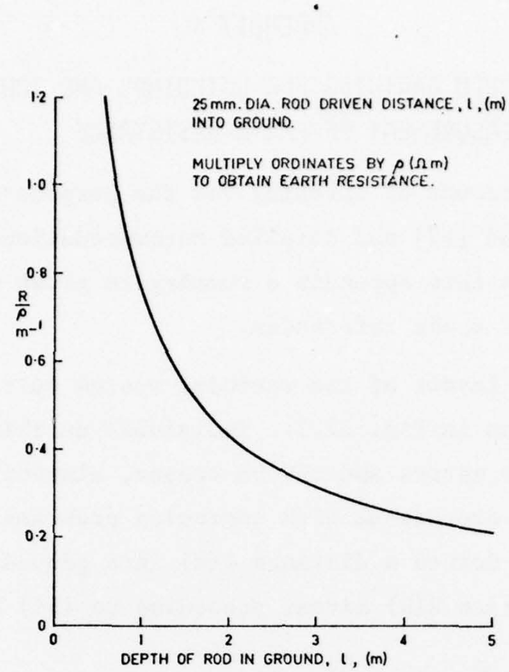


Fig. A4.1 Relation between earth resistance of driven rod, 25mm dia., and depth driven into ground.

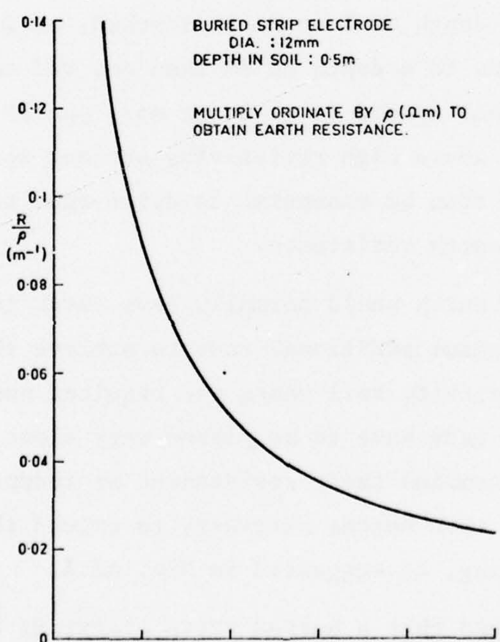


Fig. A4.2 Relation between earth resistance of buried strip 12mm dia., buried 0.5m into ground, and length of strip.

The manner in which R/ρ varies with ℓ for a 12mm dia. rod buried 0.5m below the surface is shown in Fig. A4.2.

Where the combination of driven rod electrodes adjacent to the building foundations, and additional buried strip electrodes, (for example, four strips radiating from each corner of the building) is insufficient to provide the required earth resistance it will be necessary to consider the methods outlined in Appendix 5 for very high resistivity areas.

For steel lattice towers, basically the same earthing techniques may be applied. An earth stake adjacent to each tower leg, and linked to the leg may be adequate in low resistivity areas. For areas of higher resistivity, extension of the earthing network by the methods outlined above will be necessary, i.e., additional driven rods, or buried strip electrodes radiating from each tower leg, or both.

The manner in which the effectiveness of multiple driven rods decreases as the rod-to-rod spacing decreases is discussed in [56] where the percentage increase in earth resistance of individual rods is given as a function of rod-to-rod spacing. This information is reproduced in Fig. A4.3. It appears that it could be applied, for example, to a number of driven rods along a line, as in Fig. A2.1 .

For preliminary calculations, it may be useful to have an approximate value of resistivity, depending on the type of soil or rock. Some typical values given in [56] are reproduced in Table A4.1. It is pointed out in [56] that soil resistivity may be highly moisture and temperature dependent. Clay with $\sim$ 15% moisture varies from $\rho = 72\Omega$ m at 20°C to $\rho \simeq 790\Omega$m at -5°C. For a sand/clay mixture, ρ varies from $10^7\Omega$m at zero moisture content to 42Ω m at 30% moisture.

Methods and instrumentation for earth resistance measurements are given in [7] and [56].

TABLE A4.1 (FROM [56])

TYPICAL VALUES OF RESISTIVITY OF SOME SOILS AND WATERS

Type of soil or water	Typical resistivity Ω m	Usual limits Ω m
Seawater	2	0.1- 10
Clay	40	8- 70
Ground, well and spring water	50	10- 150
Clay and sand mixtures	100	4- 300
Slates, shale, sandstone, etc.	120	10- 1,000
Peat, loam and mud	150	5- 250
Lake and brook water	250	100- 400
Sand	2,000	200- 3,000
Moraine gravel	3,000	40- 10,000
Ridge gravel	15,000	3,000- 30,000
Solid granite	25,000	10,000- 50,000
Ice	100,000	10,000-100,000

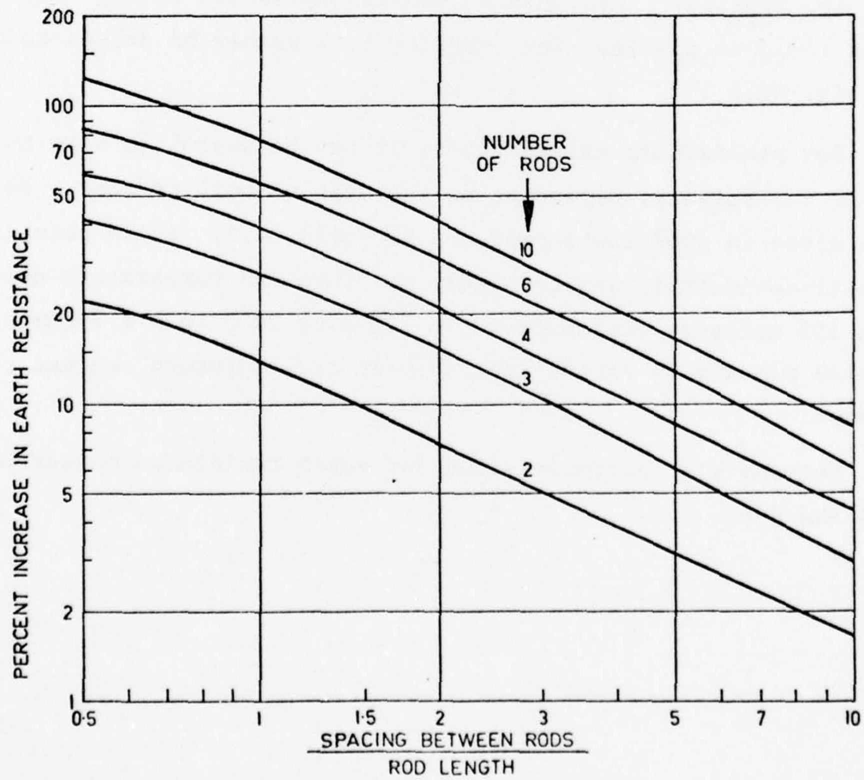


Fig. A4.3 Relation between percentage increase in earth resistance of an array of rods driven into ground and the ratio spacing between rods to rod length in ground. Adapted from [56].

APPENDIX 5

SPECIAL EARTHING ARRANGEMENTS FOR HIGH RESISTIVITY AREAS

In situations where the recommended target earth resistances for buildings, towers, etc. cannot be obtained with reasonable numbers of driven rod or buried strip electrodes, it will be necessary to adopt the alternative strategy of creating a common earth system for the complete installation. The objective here is to prevent dangerous differences of potential anywhere within the installation, even though the entire earthing system is momentarily raised to a high potential. This type of situation occurs, for example, in installations on rocky mountain tops where the high resistivity of the rock prevents satisfactory earthing by conventional methods.

Recommendations for a common earthing system for this type of situation are contained in [60]. The use of a common earth for incoming power and communication services may conflict with the codes or regulations of the relevant authorities. Nevertheless it is considered important to implement the proposal in the interest of equipment survival and personnel safety.

The common earth system should be created by linking together the earths of the various buildings, towers, etc., that make up the complete installation. The links should have resistance sufficiently low to prevent dangerous potential differences (or potential gradients) between any two parts of the installation when carrying the largest lightning current under consideration (e.g. 80 or 100kA). This earthing system would normally be linked by downleads to overhead shield wires used to protect the installation from direct strikes, and should be arranged to intercept ground currents from strikes outside the installation.

If the overall earth resistance of the complete installation were still excessive despite the measures outlined above (this could occur, for example, if the hill top were composed mainly of quartzite), it would be necessary to run an additional buried strip conductor to a remote site of lower resistivity.

APPENDIX 6

CALCULATION OF LIGHTNING-CAUSED CURRENTS AND VOLTAGES IN TYPICAL STRUCTURES

A lightning strike to an elevated object such as a mast or tower or tall building, causes injection of current having the characteristics described in Ch. 2. The consequent variation of voltage in the object depend in a complicated way on the current waveshape and the geometry and other properties of the object. The values of the time to current peak or crest, t_C, and the time required for an electromagnetic wave to travel from the top of the object to earth and back t_W are important in determining the current/voltage relationship. If $t_W << t_C$, corresponding to an object, say, less than 20m high, the potential of the top of the object will be determined mainly by a combination of the resistance and inductance of the object, and the resistance of the earth connection. An approximate equivalent circuit is shown in Fig. A6.1. The distributed capacitance to earth of various parts of the object is represented by one or more lumped capacitance elements as shown; these may affect the potential in some situations.

Where t_W and t_C are of the same order of magnitude, the system becomes more difficult to analyse, as the travelling waves of current and voltages have a dominant effect on the potentials at various parts of the system in the first few microseconds of the lightning stroke current injection. This is the type of situation that exists in the steel lattice towers of high voltage power transmission lines, of the order of 30m or more high. A number of authors have analysed this situation in relation to the lightning performance of these lines [61, 62, 63 and 64], to which the reader is referred for detailed treatments. It will suffice for the present purpose to summarise the main conclusions reached by these authors that appear relevant to the estimation of peak voltages at the top of structures such as microwave towers and antenna masts.

In [64] it is shown that the variation with time of tower top potentials can be calculated using travelling wave methods, assuming earth and tower have infinite conductivity, no corona effects, waves of charge and current travel at the velocity of light, and current waves maintain their waveshape as they travel.

For each individual travelling wave, the voltage/current relationship is expressed as a surge impedance. Where the current wave can be approximated as a ramp commencing at $t = 0$, and the object can be approximated as a cylinder of height h, radius r, it is shown that the surge

impedance is given by

$$Z \simeq 60 \log_e(\sqrt{2}\,\frac{2h}{r}) - 60 \text{ ohm} \tag{A6.1}$$

provided ct >> r and h >> r.

Where the object can be approximated as a right circular cone, the surge impedance is given by

$$Z \simeq 60 \log_e(\sqrt{2}/S) \text{ ohm} \tag{A6.2}$$

where S is the sine of the half angle of the cone.

The validity of the methods given in [64] was confirmed by actual potential measurements in scale model tests. In particular, the response of a steel lattice tower of a type used for a high voltage transmission line was determined. The more important aspect of the results obtained is the manner in which the peak tower top potential is related to the tower surge impedance, and the time to crest, t_c of the current wave. This relationship is shown in Fig. A6.2, adapted from Fig. 3 of [64].

As an example of the application of these relations, consider a steel lattice tower of height about 30m (similar to the structures analysed in [64]) representable as a cone of half angle 5°, subjected to a current impulse rising to peak value I_m in 2.5 μs. From (A6.2) the surge impedance is approximately 170 ohm, and the peak tower top potential would be about 26 V/A from Fig. A6.2, i.e. 26 I_m volt. For a peak current of 80kA assumed as the "worst case" situation, the peak tower top potential is about 2MV.

Estimates of this type are probably accurate enough for the purpose of selecting insulating levels, specifying clearances, etc. Where more detailed information of the time variation of potential is required, travelling wave calculations as described in [65] would have to be undertaken.

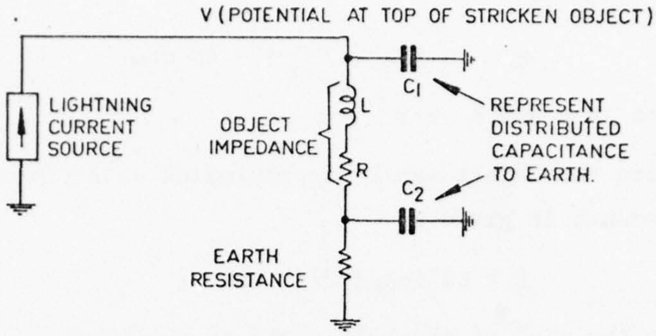


Fig. A6.1 Approximate equivalent circuit of an electrically short object struck by lightning.

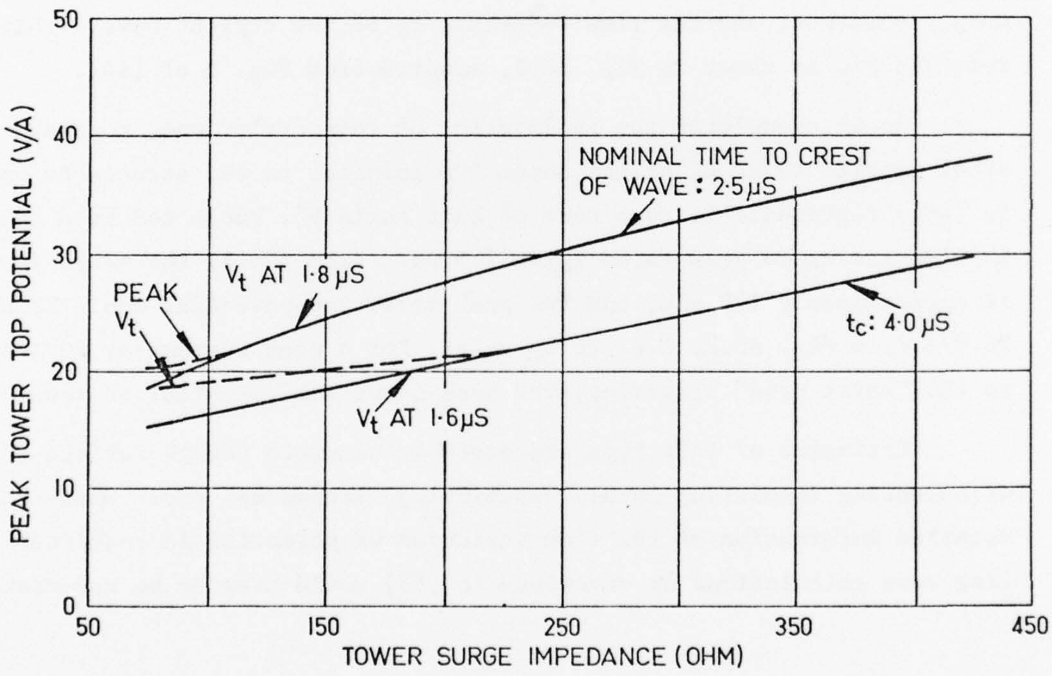


Fig. A6.2 Relation between peak tower top potential and tower surge impedance for steel lattice towers of the type used in high voltage transmission lines. Adapted from Fig. 3 of [64]. *V_t = peak tower top potential.*

APPENDIX 7

CALCULATION OF INDUCED SURGE IN A SIGNAL CONDUCTOR

In the situation shown in Fig. 12 the signal conductors connecting equipment in separate parts of an installation are protected from direct strike by the overhead shield wire. Flashover to the signal conductors from a stricken part of the system is prevented by maintaining adequate clearances and by low resistance earthing. At each end, it will be assumed that the signal conductors enter a portion of the installation (building, etc.) where no voltage surge can be induced by lightning. The recommended protection in this situation is shown in Figures 25 to 32, depending on the type of signal under consideration.

The expected behaviour of this protective system can be assessed in terms of the approximate equivalent circuit shown in Fig. A7.1 (p.81). The lightning current injection is represented by a current source, with peak current I_m and front time of t_f. Assume that the shield wire is earthed at intervals of ℓ metres, each earth stake has resistance R_e to earth, and that the current is entirely discharged by n earth stakes along the length of the signal conductor.

Then the resistance to earth is R_e/n, from shield wire to earth, and the voltage on the shield wire will rise to $I_m\ R_e/n$ in t_f seconds, assuming the system is electrically short. This voltage will be coupled to the signal conductor through the capacitance, C_c. The lightning current flowing through the shield wire to the earth stakes will cause a longitudinal induced voltage in the signal conductors because of the mutual inductance. These two voltage sources will be considered separately.

The capacitance C_c can be estimated from

$$C_c/n\ell \simeq \pi\varepsilon/\log_e(d/a)\ \mathrm{F/m}. \qquad \text{(A7.1)}$$

where d is the separation and a the radius of the conductors. For $a \simeq 4$mm and $d \simeq 1$m, $C_c/L \simeq 5 \times 10^{-12}$ F/m; $n\ell$ is the distance over which coupling exists between shield wire and signal conductor.

Assuming the signal conductor is held at approx. earth potential by a protective device carrying a current I_s, then

$$\begin{aligned} I_s &= C(dV/dt) \\ &= C_c\ (\Delta V/t_f) \\ &= C_c\ (R_e/n)(I_m/t_f) \\ &= \frac{\pi\varepsilon n\ell\ R_e\ I_m}{[\log_e(d/a)]n\ t_f}\ . \end{aligned}$$

So, $$I_s \simeq \frac{\pi\varepsilon\ell\ R_e\ I_m}{[\log_e(d/a)]t_f} \qquad \text{(A7.2)}$$

For $\pi\varepsilon/\log_e(d/a) \simeq 5 \times 10^{-12}$ F/m, $\ell = 20$m, $R_e, = 20\Omega$, $I_m = 80$kA, and $t_f = 10^{-6}$s,

$$I_s \simeq 5 \times 10^{-12} \times 20 \times 20 \times 80 \times 10^3/10^{-6}$$
$$\simeq 160\text{A (flowing for } 1\mu\text{s)}$$

Note that this current is independent of the length over which coupling exists provided ℓ is constant, i.e. the shield wire is earthed at regular intervals.

The worst situation for causing a longitudinal voltage exists when the shield wire is struck near one end, and the surge current flows one way along the shield wire, each earth stake carrying $1/n^{th}$ of the current. The mean current in the shield wire is then one half the stroke current injected, see Fig. A7.1. From [66] the mutual inductance, M, is given by

$$M/n\ell \simeq \frac{\mu_o}{2\pi} \log_e \frac{d'}{d} \text{ (H/m)}, \qquad \text{(A7.3)}$$

and the self inductance is given by

$$L/n\ell = \frac{\mu_o}{\pi} \log_e \frac{2h}{a} \text{ (H/m)} \qquad \text{(A7.4)}$$

The mean value of dI/dt along the shield wire is

$$dI/dt = \frac{1}{2} I_m/t_f \text{ A/s, for } t = 0 \text{ to } t_f. \qquad \text{(A7.5)}$$

Hence the longitudinal induced voltage

$$= M\ \overline{dI/dt} \qquad \text{(A7.6)}$$

Assume as before that a protective device holds the signal wire at approximately earth potential by carrying current I_s. The equivalent circuit of this system consists of a voltage source $M\ \overline{dI/dt}$ for time t_f in series with the self inductance of the signal wire, L.

$$\text{As } L\ (dI_s/dt) = M\ \overline{dI/dt} \qquad \text{(A7.7)}$$

$$I_s = \frac{M}{L}\int_o^{t_f} \overline{dI/dt}\ dt = \frac{M}{L}\,\frac{\frac{1}{2}\ I_m}{t_f}\,t_f$$

So, $$I_s = \frac{M\ I_m}{2L} \qquad \text{(A7.8)}$$

Substituting from (A7.3) and (A7.4),

$$I_s = \frac{n\ell\ (\mu_o/2\pi)\log_e(d'/d)}{2n\ell(\mu_o/2\pi)\log_e(2h/a)}\ I_m = \frac{\log_e\ (d'/d)}{2\ \log_e(2h/a)} I_m. \qquad \text{(A7.9)}$$

Typical values are

$$d' = 5m,\ d = 1m,\ h = 3m,\ a = 4mm$$

Whence

$$I_s \simeq 0.1\ I_m \qquad (A7.10)$$

For I_m = 80kA, $I_s \simeq$ 8kA, showing that a gas arrester is the best choice of protective device, having a rapid breakdown and a current capacity of about 10^4A.

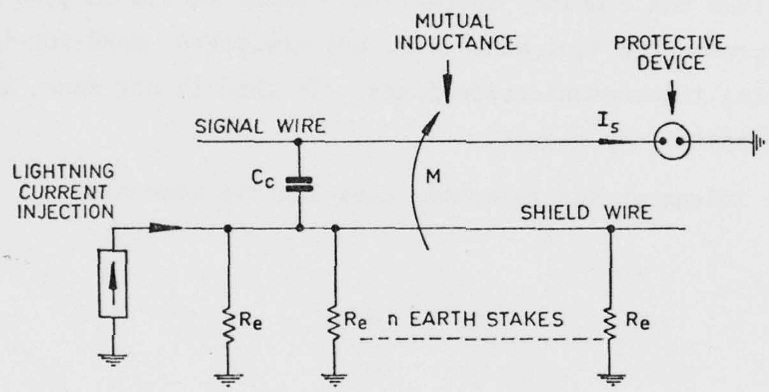


Fig. A7.1 Approximate equivalent circuit for coupling between a stricken shield wire and a signal wire.

APPENDIX 8

PROTECTION OF TELECOMMUNICATION LINES

A comprehensive review of the lightning protection of telecommunication lines is given in a manual published by C.C.I.T.T.* Study Group V, [67]. Detailed recommendations for application in Australia are given in internal documents of Australian Telecommunication Commission [58] and [68]. A review of recent developments in lightning protection in Australia is given in [69].

While details of the lightning protection of incoming telecommunication services must, of course, be left to the appropriate authority, some special consideration should apply where the installation served has an earthing problem, as in a high resistivity area. If the strategy suggested in Appendix 5 has to be adopted, then the combined installation earth should be used as the earthing point for protective equipment (e.g. gas arresters) used for the protection of incoming telecommunication lines. If this is not done, danger to personnel and equipment may result.

* The International Telegraph and Telephone Consultative Committee

APPENDIX 9

RECOMMENDED FAULT REPORTING FOR LIGHTING-CAUSED FAULTS

The following information should be supplied.

1. Identification of damaged part(s).
2. Description of nature of damage.
3. Observation of any consequent damage to other components or equipment.
4. Route by which lightning-caused surge reached equipment.
5. Nature of protective devices, if any, and reason for failure of protective system.
6. Description of weather conditions at time of occurrence of fault, e.g. occurrence of nearby lightning flashes to ground.